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# Anti-Icing in Gas Turbines

**Majed Sammak**

Thesis for the Degree of Master of Science

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# Abstract

This thesis gives a thorough description of the icing mechanisms in gas turbines, the underlying physics of ice and ice types that can form in gas turbines. The primary intention of this thesis is to investigate the icing condition regions leading to ice formation in gas turbines.

The icing problem in gas turbines is explained in detail in this thesis. The different ice types, icing mechanism in gas turbines and ambient conditions leading to icing are reported. Ambient factors and other factors that can affect icing conditions are also discussed. The icing conditions have been investigated for different air velocities in the inlet system of the gas turbine and with various ambient conditions. A recovery factor has been used in the calculations of icing conditions. The recovery factor gives the icing surface temperature which lies between the air static temperature and air total temperature. The recovery factor differs from laminar till turbulent flow. The experimental value 0, 8 is taken in the calculations. Ice formation locations in the gas turbines' inlet systems are also covered. My study to the icing mechanism in gas turbines shows that there is no hazard for icing when air velocity is very high because of great air temperature depression. Furthermore, as long as the surface temperature is above the water saturation temperature, condensation will not occur and ice will not form even if the surface temperature is below freezing point temperature. The highest risk of ice building lies specifically between the highest and lowest velocity, in contrast to what was believed earlier that the risk lied at highest velocity.

A possible solution to the icing problem in gas turbines is also presented in this thesis. The different anti icing systems that can protect the gas turbine is investigated. I focused mainly on the compressor bleed heating system and hot water heat exchanger system in my calculations. The heat power that is needed to warm up the incoming air to the gas turbine has been calculated for two Siemens gas turbines; SGT-700 that is using the compressor bleeds anti-icing system and SGT-800 that is using a water heat exchanger anti-icing system. The results show that the compressor bleed anti-icing system has a larger influence on gas turbine performance than the hot water heat exchanger. The pulse jet self cleaning filter is also mentioned in this part to explain why pulse filter has been used as an anti-icing system.

# Contents

# Nomenclature

## Abbreviations

| | |
|---|---|
| FOD | Foreign object damage |
| GT | Gas turbine |
| H.E | Heat exchanger |
| IGVs | Inlet guide vanes |
| LWC | Liquid water content |
| KE | Kinetic energy |
| RH | Relative humidity |
| RF | Recover factor |
| SFC | Specific fuel consumption |
| SGT | Siemens gas turbine |

## Latin

| | |
|---|---|
| a | Droplet radius [cm] |
| A | Area [$m^2$] |
| C | Velocity, Absolute velocity [m/sec] |
| $C_u$ | Absolute tangential velocity [m/sec] |
| $C_z$ | Axial component of velocity [m/sec] |
| $c_{p,v}$ | Specific heat capacity at constant pressure and volume [kJ/kg.K] |
| *f* | Fuel/air ratio by weight [-] |
| g | gravity [$m^2$/sec] |
| h | Specific enthalpy [kJ/kg] |
| k | Specific heat ration $C_p/C_v$ [-] |
| m | Mass flow [kg/sec] |
| M | Mach number [-] |
| P | Pressure [bar] |
| $P_\upsilon$ | Partial pressure [bar] |
| Pr | Prandtl number [-] |
| Q | Heat transfer [kw] |
| $Q_{net,p}$ | Net calorific value at constant *P* [kJ] |
| r | Pressure ratio [-] |
| R | Gas constant [kJ/kg.K] |
| t | Temperature ratio, Temperature [-], [$C^o$] |
| T | Temperature [$C^o$] |
| U | Compressor rotational speed [m/sec] |
| W | Relative velocity [m/sec] |
| $W_u$ | Relative tangential velocity [m/sec] |
| $W_N$ | Specific work (power) output [kw s/kg] |
| V | Velocity [m/sec] |
| Z | Elevation [m] |

## Greek letters

| | |
|---|---|
| $\alpha$ | Absolute air angel |
| $\beta$ | Relative air angel |
| $\gamma$ | Ratio of specific heats [-] |
| $\eta_c$ | Compressor efficiency [%] |
| $\eta_t$ | Turbine efficiency [%] |
| $\omega$ | Absolute humidity [kg water vapour/kg dry air] |
| $\phi$ | Relative humidity [%] |
| $\rho$ | Density [kg/m$^3$] |
| $\sigma$ | Surface tension [N/m] |
| $\upsilon$ | Volume fraction [-] |

## Subscripts

| | |
|---|---|
| 0 | Stagnation value |
| 1,2,3, etc. | reference planes |
| a | Ambient air |
| c | Compressor |
| dp | dew point |
| f | Fuel |
| g | Gas |
| i | in |
| o | out |
| N | Net power |
| in | In of the control volume |
| out | outlet of the control volume |
| t | Turbine |
| u | The tangential component |
| v | water vapour |
| wa | wall or surface |
| s | Static |
| z | The axial component |

## Superscripts

| | |
|---|---|
| ˙ (dot) | Quantity per unit time |
| ´ (ditch) | Real process |

# 1. Introduction

Gas turbines manufactured by Siemens Industrial Turbomachinery AB operate in many different areas with extreme environments. They run in Polar Regions and tropics, in deserts and at seas. In order to make these turbines run with full performance and reliability, the consumed air must be treated. In cold environments many problem can appear during operation of the gas turbine. These problems can be determining the suitable lubricating oil for cold environments as well as the desirable material that can tolerate very low temperatures e.g -40 [$C^o$]. One of the most important objectives in gas turbines that operate in arctic environments is avoiding ice formation in the turbine inlet systems (Fig. 1.1).

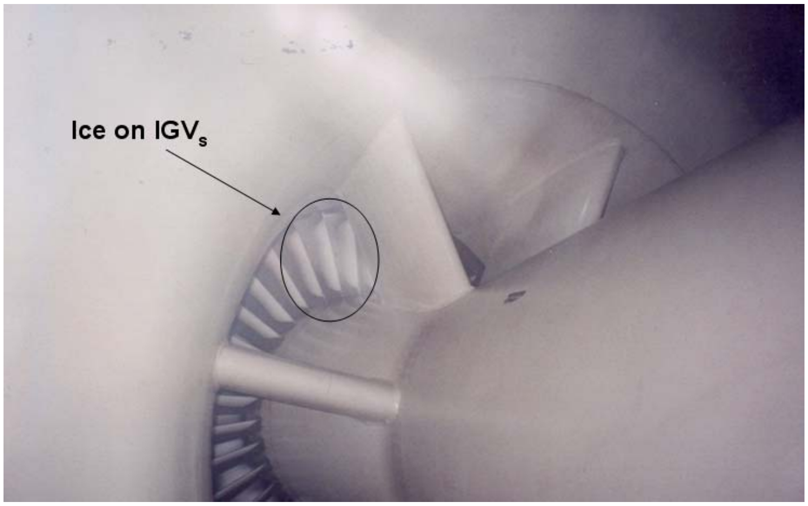

**Figure 1.1 Ice on $IGV_s$**

If ice builds in the gas turbine, great consequences can result. Icing can plug the inlet filtration system causing an increase in pressure drop in the inlet system which leads to performance loss. In extreme cases, ice can build up on bellmouth or $IGV_s$, risking foreign object damage (FOD). Several anti-icing systems have been designed to inhibit ice formation on inlet components in order to protect the gas turbine from these hazards.

## 1.1 Problem definition

This master thesis is initiated by Siemens Industrial Turbomachinery AB, Finspång, Sweden to shed a light on the icing mechanism in their gas turbines. The aim of this master thesis is to identify different ice types that can arise in gas turbines and identify the different ice types that constitute a hazard to these turbines. The work was also initiated to understand the ambient conditions, namely ambient temperatures and relative humidities that give rise to specific icing problems in gas turbines. Siemens Industrial Turbomachinery AB has applied various imprecise icing conditions to its gas turbines. Some of these installations have run successfully under these conditions and other did not. It was therefore of essential value to come out with more specific icing conditions.

Siemens Industrial Turbomachinery AB wishes to have more information about different anti-icing systems that can protect its gas turbines from icing. The aim is also to realize what heat power is needed to avoid ice formation in two of their gas turbines; SGT-700 and SGT-800. Two anti-icing systems are thoroughly investigated, namely the compressor bleed anti-icing system and hot water heat exchanger system.

Siemens' experiences with pulse jet self cleaning filters showed that pulse filters can be used as a working anti-icing system but there was no reasonable explanation for this. There was also a need to understand the pulse filter behavior.

## 1.2 Background

Ice takes different forms in the gas turbine depending on the combination of ambient temperature and relative humidity. There are many factors that can lead to ice building. These factors are e.g. ambient temperature, air velocity, humidity and droplets size. Icing may build up on different places on the inlet system but it's more likely that they do on the inlet filtration system, bell mouth and inlet guide vanes. The icing can increase the pressure drop in the inlet complements, leading to performance losses. It can also block the inlet filtration equipment, causing the gas turbine to ingest unfiltered air. In extreme cases pieces of ice may even be ingested in the compressor which causes Foreign Object Damage (FOD). Thus protection the gas turbine from ice formation is very important to extend a gas turbine's life.

It is very important to equip the gas turbine with an ice protection system. An ice protection system may be an anti- or a de-icing system. The requirements for such systems are reliability, optimization and reduction of unnecessary power and efficiency losses. Such systems include the heating systems, chemical systems, pulse filter system and other systems. Selection of a specific system depends on the profit as well as the application of the gas turbine. Sensors can be used to help those systems run on time. By applying sensors, the heat necessary to prevent the turbine from icing is only activated upon icing formation. These sensors are usually installed in the critical areas for ice formation. There are two categories of sensors; sensors that measure the conditions of ice creation in the turbine and sensors that detect ice building.

## 1.3 Objectives

One of the general objectives of this thesis has been to investigate the icing mechanism in the gas turbine and figure out the icing conditions that lead to ice formation in gas turbines. Siemens Industrial Turbomachinery AB wishes to learn more about different anti-icing systems that can be used to inhibit icing in its gas turbines. Compressor bleed anti-icing system and hot water heat exchanger are of special interest and Siemens want to investigate these systems on the gas turbines SGT-700 and SGT-800. The master thesis plan can be separated into three sections.

I. Gathered information about ice types and icing mechanism
    - Identifying different ice types that can arise in gas turbines and find the ice type that can constitute a hazard in the gas turbines.
    - Shed a light on the icing phenomena in Siemens gas turbines.
    - Study icing conditions in two kinds of Siemens gas turbines (a one-axial-turbine SGT-700 and a two-axial-turbine SGT-800).

II. Study different anti-icing systems and doing calculations for deciding the heat power
    - Doing a literature survey for different anti-icing systems that can protect Siemens gas turbines from icing.
    - Doing calculations to receive the required heat power to avoid ice formation in the gas turbines.
    - Finding out where the icing phenomena rise in account of sensor installation.
    - Trying to give a reasonable explanation to the pulse filter behavior as anti-icing system.

## 1.4 Limitations

The limitations in this study can be divided into two parts. The first part is limitations known from the beginning of the thesis. This subject is very broad and it’s difficult to cover the all points. These limitations are:

- The work will investigate anti-icing systems in only two Siemens gas turbines; SGT-700 and SGT-800.
- The calculations will only be done for two anti-icing systems; compressor bleed anti-icing system and hot water heat exchanger system.
- There will not be any experiments for these systems. It is purely a theoretical study.

Under my studying and researching in this subject I came across other limitations due to lack of time or difficulty in implementation.

- It wasn’t possible to take in account in my calculations the water droplets trajectories because they have very complex equations and I didn’t have the tool to solve them. For more information I recommend reading reference [37].
- We couldn’t manage to measure the surface temperature of the icing surface during my master thesis period.

## 1.5 Methodology

Siemens Industrial Turbomachinery AB would like to have a deeper understanding for icing mechanism and different ice types that can be present in its gas turbines. Icing conditions that lead to icing problem are also one of Siemens requirement for this thesis. Siemens also wishes to get more information about different anti-icing systems that can be used to protect its gas turbines from icing. By doing calculations, it would be possible to come up with the necessary heat power that is needed to inhibit icing. Therefore I used different methodologies in this thesis to achieve Siemens requirement and to fulfill my work.

The first methodology covers the literature survey that includes ice literature, filter literature, anti-icing system literature and sensors literature. My techniques to approach this information were

- Ice literature: I didn't find enough information about icing mechanisms in stations gas turbine open literature. Therefore I began to search in the metrology field. I contacted Metrology Institution Stockholm University "MISU" for more information and read many articles about aircraft icing. My source to this information was open literature in the internet.
- Filter literature: Information was gathered from open literature. ASME paper, publications from companies and many contact people from Siemens.
- Anti-icing system literature: Information was obtained from ASME paper and conference paper.
- Sensor literature: I got this information from ASME paper and publications from companies.

During my thesis in Siemens, many interviews and discussions were held with people who worked with these topics or had information or experience in this field.

The second methodology treats the calculation techniques. In my master thesis I calculated the icing condition regions and heat power for two anti-icing systems.

- Icing conditions calculations are based on thermodynamics and I did these calculations with the help of Excel.
- Heat power calculations have been done with the help of two programs; Excel and a Siemens internal program called GT-Performance. GT-Performance generates data about gas turbine characteristics by feeding the in-data of the gas turbine.

My icing conditions results were discussed with many experts and installation engineers who have experience with icing in the gas turbines. During my master thesis we tried to do a test to measure the surface temperature but unfortunately we didn't manage. Results from calculations in this report are approximate since the icing conditions regions are only based on thermodynamic. The behavior of water droplets in the gas turbine and water droplets trajectories are not taken into account. The recovery factor established is also theoretical. A practical measurement has to be done to obtain the surface temperature and the recovery factor. The results give a clearer picture about icing conditions that are likely to result in icing in the gas turbines and explain the heat power that is needed to avoid icing. For deeper information about the calculations, references [40, 41] are recommended.

## 1.6 Outline of the thesis

This master thesis can be taken as one unit. The theory part is needed to understand the calculations. Chapter one gives a brief introduction to the subject. In chapter two the introduction to general knowledge of the gas turbine is presented. Chapter three deals with general factors that effect icing. Chapter four is a brief introduction to ice, ice types and ice collection efficiency. Chapter five presents the thermodynamic theory behind my calculations. I here explain ice physics and mechanisms in gas turbines and the recovery factor concept. These five chapters form the background to the icing conditions calculations. Chapter six demonstrates the air's effects on gas turbines. In chapter seven the gas turbine inlet air system is described. Chapter eight illustrates different anti-icing systems. Chapter nine presents the icing condition regions calculations. In chapter ten, heat power calculations are presented. Chapter eleven summarizes different ice sensors that are used in gas turbines. Chapter twelve is the conclusion. Chapter thirteen gives a presentation of possible future developments that can be done in this field.

## 1.7 Acknowledgements

This work is supported by Siemens Industrial Turbomachinery AB in Finspång, Sweden. I would like to express my gratitude to all the people involved in this project. Thanks for my supervisors in Siemens Kerstin Tageman and my group manager Lennart Näs for giving me the opportunity to take part in such an interesting field and for their invaluable support and guidance throughout the project.

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This work could not have been completed without help and contributions from many individuals in Siemens Industrial Turbomachinery AB.

I would also like to dedicate a word of thanks to all my colleagues at work for the assistance and interesting discussions throughout the work, especially Magnus Genrup, Jesper Håkansson, Mats G. Sjödin, Christer von Wowern, Åke Klang, and everyone else in the GRPP departments, in many ways making this thesis possible.

I dedicate this work to my beautiful wife Enas who has always stood by my side. She is the source of my inspiration and encouragement. I would like to thank her for all love she surrounds me with.

My biggest love and admiration goes to my father and mother who taught me to always reach for the stars and helped me follow my dreams. Though miles away, they are always in my heart. I would also like to dedicate a word of thanks to my sister and brother. Their encouraging voices always echoes in my heart and I wish them a beautiful and successful life.

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Eng. Suleyman and Dr. chafik with his fiancée Zahra. In Lund University I have met great people that I would like to thank, especially Jaime Arriagada, Baris and Merzad.

Last but not least I would like to express my gratitude and love to my aunt and grandmother in Sweden who welcomed me into their homes and made Sweden so much warmer.

Finspång, February 2006

## 1.8 Siemens Industrial Turbomachinery AB

Finspång has been delivering equipment for power generation for more than100 years. The origin is partly the company DeLaval Ångturbin AB in Nacka, which started its business 1893. 1913 the two Brothers Birger and Fredrik Ljungström began to manufacture their own counter-rotating radial steam turbine in Finspång, under the company name Svenska Turbinfabricsaktiebolaget Ljungström (STAL). In the late 1950's the two companies DeLava land STAL were merged, and the business in Nackawa moved to Finspång.

Siemens Industrial Turbomachinery AB in Finspång, that has established 2003, employs around 1850. It's the largest division is Gas Turbines with some 1260 employees in Finspång. In terms of products, the medium gas turbines, SGT-500 (formerly known as GT35C), SGT-600 (fka GT10B), SGT-700 (fka GT10C) and SGT-800 (fka GTX100), are the most prominen

# 2. Gas turbine system theory

## 2.1 Introduction

The simplest form of a gas turbine is when it consists of its three main components; a compressor, a combustion chamber and a turbine connected together as it shown diagrammatically (Fig. 2.1). The basic purpose of the compression system in a gas turbine is to provide the required cycle pressure ratio to the working fluid. The compression system is therefore integral to the thermodynamic cycle of the gas turbine [2]. The cycle is known as the Brayton (Joule) cycle. The compressor does work on the fluid to increase its enthalpy from an initial value at thermodynamic state 1 to a higher value at state 2. After this the compressed air directed to the combustion chamber where fuel is added from state 2 to 3. The mixture is burned at constant pressure. The high pressure and high temperature combustion gases expand through the turbine to the surrounding state 3 to 4, producing power [3].

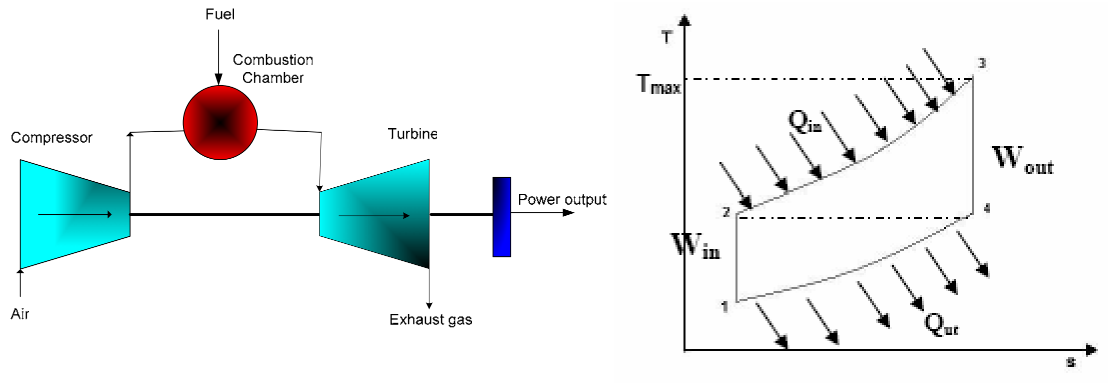

**Figure 2.1 Simple gas turbine cycle**

In the T-S diagram above, the area enclosed by the process represents the net work output. The net work output can either be used as a mechanical drive or be used to turn generator that produces electricity.

## 2.2 The Ideal gas turbine cycle

The ideal cycle for the simple gas turbine is the Joule cycle. Since it is an ideal cycle it means that the theoretical performance calculated from it can not be reached in practice. The assumption of ideal gas turbine cycles conditions are [2].

1. Compression and expansion processes are reversible and adiabatic (isentropic) (Fig. 2.2).
2. The change of kinetic energy of the working fluid between inlet and outlet of each component is negligible (ΔKE=0).
3. There are no pressure losses in the inlet of combustion chamber, heat exchangers, intercoolers and exhaust ducting (Δp=0)

4. The working fluid has the same composition throughout the cycle and is a perfect gas with constant specific heats ($C_p$ & $C_v$ = constant).
5. The mass flow of gas is constant throughout the cycle.
6. Heat transfer in a heat-exchanger is complete (No heat losses in heat exchangers $\Rightarrow$ max $\Delta Q$ from hot to cold side).

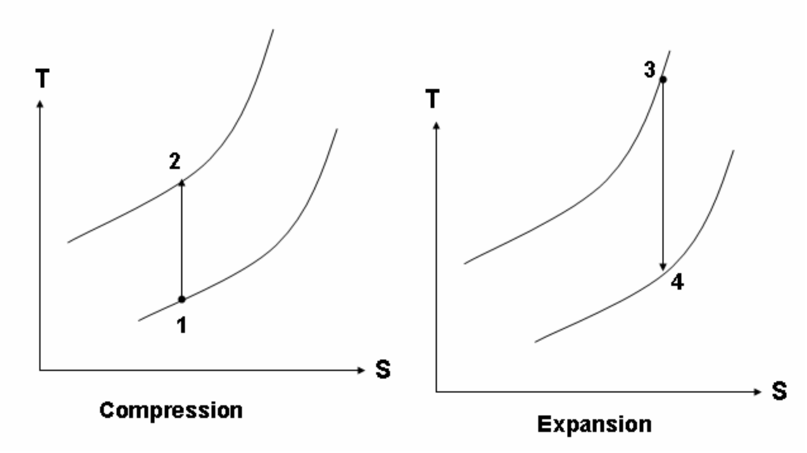

**Figure 2.2 Ideal compression and expansion process**

The relevant steady flow energy equation is

$$Q - W = \sum m_{out} \cdot \left( h_{out} + \frac{C_{out}^2}{2} + g.z_{out} \right) - \sum m_{in} \cdot \left( h_{in} + \frac{C_{in}^2}{2} + g.z_{in} \right) \qquad (2.1)$$

With assumption of an ideal cycle we get

$$Q = (h_2 - h_1) + \frac{1}{2} \underbrace{(C_2^2 - C_1^2)}_{=0} + W \qquad (2.2)$$

Q and W are the heat and work transfers per unit mass flow. Applying this equation to each gas turbine component, we get adiabatic compression and expansion:

$$W_{compressor} = - (h_2 - h_1) = - C_p (T_2 - T_1) \qquad (2.3)$$

$$W_{compressor} = - (h_3 - h_4) = - C_p (T_3 - T_4) \qquad (2.4)$$

And the heat input will be

$$Q_{combustion\ chamber} = - (h_3 - h_2) = - C_p (T_3 - T_2) \qquad (2.5)$$

The cycle efficiency is ratio between net work output and heat supplied

$$\eta = \frac{C_p(T_3 - T_4) - C_p(T_2 - T_1)}{C_p(T_3 - T_2)} \qquad (2.6)$$

From the isentropic p-T relation

$$\frac{T_2}{T_1}=\left(\frac{P_2}{P_1}\right)^{\left(\frac{(\gamma-1)}{\gamma}\right)}=r^{\left(\frac{(\gamma-1)}{\gamma}\right)} \qquad , \qquad \frac{P_2}{P_1}=\left(\frac{T_2}{T_1}\right)^{(\gamma/(\gamma-1))}$$

r: is the pressure ratio $\frac{P_2}{P_1}=\frac{P_3}{P_4}$

In an ideal cycle $P_1=P_4$ and $P_2=P_3$

$$\Rightarrow \frac{P_2}{P_1}=\frac{P_3}{P_4}\Rightarrow\frac{T_2}{T_1}=\frac{T_3}{T_4}\Rightarrow\frac{T_4}{T_1}=\frac{T_3}{T_2}$$

Re-writing the expression of efficiency

$$\eta=\frac{C_p(T_3-T_4)-C_p(T_2-T_1)}{C_p(T_3-T_2)}=\frac{T_3-T_4-T_2+T_1}{T_3-T_2}=\frac{T_3-T_2-(T_4-T_1)}{T_3-T_2}$$

$$=1-\frac{T_4-T_1}{T_3-T_2}=1-\frac{T_4\left(1-\frac{T_1}{T_4}\right)}{T_3\left(1-\frac{T_2}{T_3}\right)}$$

We know that $\frac{T_4}{T_1}=\frac{T_3}{T_2}$

$$\eta=1-\frac{T_4}{T_3}=1-\frac{1}{\left(\frac{T_3}{T_4}\right)}$$

$$\frac{T_3}{T_4}=\left(\frac{P_3}{P_4}\right)^{\left(\frac{(\gamma-1)}{\gamma}\right)}=r^{\left(\frac{(\gamma-1)}{\gamma}\right)}$$

$$\Rightarrow \eta=1-\frac{1}{r^{\left(\frac{(\gamma-1)}{\gamma}\right)}} \tag{2.7}$$

The efficiency depends only on the pressure ratio and the nature of the gas [2].

The specific work output W is given by

$$W_N= C_p\ (T_3-T_{4)} - C_p\ (T_2-T_1) \tag{2.8}$$

By dividing work by $(C_p.T_1)$ we get specific work

$$\frac{W}{C_p.T_1}=t\left(1-\frac{\frac{T_4}{T_1}}{\frac{T_3}{T_1}}\right)-\left(\frac{T_2}{T_1}-\frac{T_1}{T_1}\right)=t\left(1-\frac{1}{r^{\left(\frac{(\gamma-1)}{\gamma}\right)}}\right)-(r^{\left(\frac{(\gamma-1)}{\gamma}\right)}-1)$$

This can be expressed by

$$\frac{W}{C_pT_1}=t(1-\frac{1}{r^{(\gamma-1)/\gamma}})-(r^{\frac{(\gamma-1)}{\gamma}}-1) \qquad (2.9)$$

## 2.3 The Real gas turbine cycle

The performance of real cycles differs from that of ideal cycles fro the following reasons [2]

1. The fluid velocities are high in turbomachinery thus the change in kinetic energy between inlet and outlet of each component cannot be ignored ($\Delta KE \neq 0$) (Fig. 2.3).

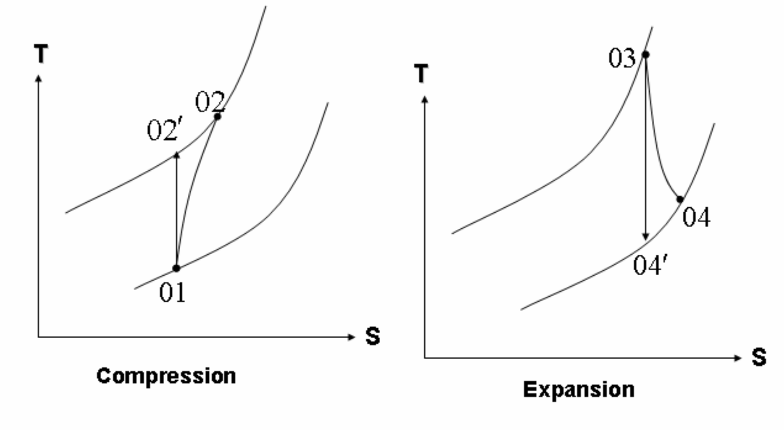

**Figure 2.3 Real compression and expansion process**

2. Fluid frication results in pressure losses in combustion chambers and heat exchangers ($\Delta p \neq 0$).
3. The compressed air cannot be heated to the temperature of the gas leaving the turbine.
4. More work that that required for the compression process will be necessary to overcome bearing and windage friction.
5. The values of $C_p$ and $\gamma$ of the working fluid vary throughout the cycle due to changes of temperature and, with internal combustion, due to changes in chemical composition.
6. Cycle efficiency needs to be defined using specific fuel consumption and lower heating value.
7. The mass flow through the turbine will be greater than that through the compressor because of the fuel mass flow which is added in the combustion chamber.

## 2.4 Compressor and turbine efficiencies

The efficiency of any machine, the object of which is the absorption or production of work, is normally expressed in terms of the ratio of actual and ideal work transfers. Because turbomachinery are essentially adiabatic, the ideal process is isentropic and the efficiency is called isentropic efficiency [2].

Compressor Efficiency

$$\eta_c = \frac{W'}{W} = \frac{T'_{02} - T_{01}}{T_{02} - T_{01}} \tag{2.10}$$

Turbine Efficiency

$$\eta_t = \frac{W}{W'} = \frac{T_{03} - T_{04}}{T_{03} - T'_{04}} \tag{2.11}$$

## 2.5 Specific fuel consumption

The performance of real cycles can be expressed in terms of the specific fuel consumption. Specific fuel consumption is fuel air ratio per unit net power output [2].

$$\mathrm{SFC} = \frac{f}{W_N} \tag{2.12}$$

*f*: Fuel air ratio, $\frac{m_f}{m_a}$

## 2.6 Heat rate

Heat rate is the heat input required to produce a unit quantity of power. It is normally expressed in kJ/kWh [2].

Heat rate = SFC. $Q_{net,p}$ (2.13)

## 2.7 Axial Compressor

### 2.7.1 Introduction

Since gas turbine is a continuous- flow device, compressors used to achieve the cycle. Compressors are classified to axial and centrifugal compressor. Axial-flow compressors consist of an alternating series of rotating and stationary rows of airfoils called rotors and stators (Fig. 2.4). The number of stages varies depending upon the pressure ratio required [2]. The compression process that occurs in each stage of an axial-flow compressor consists of two important facets. First the working fluid is initially accelerated by the rotor blades adding kinetic energy to the fluid by increasing its tangential momentum. Thus the total enthalpy and total pressure will increase. Second the fluid decelerated in the stator blade passages wherein the kinetic energy transferred in the rotor is converted to static pressure. The process is repeated as many stages as are necessary to yield the required overall pressure ratio [3].

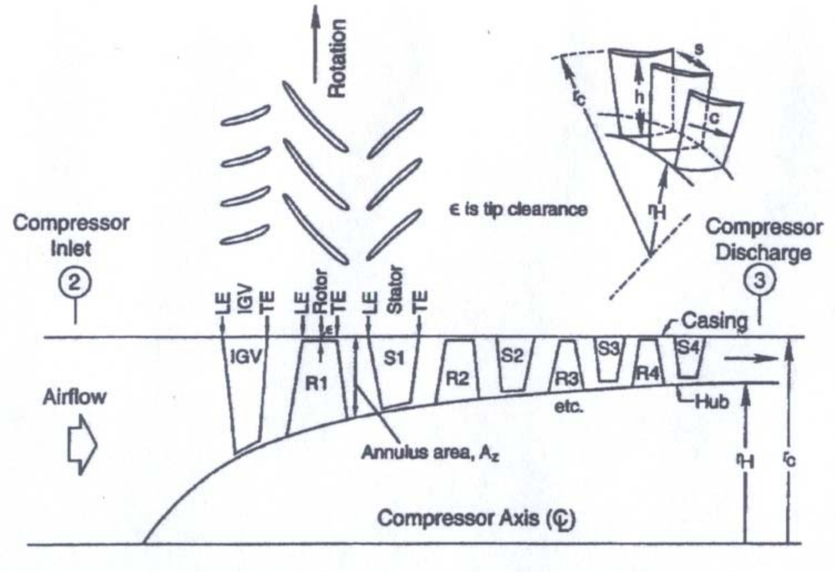

Figure 2.4 Axial compressor [3]

### 2.7.2 Stage analysis

The most important tool used to describe how compressors work aerodynamically is the vector diagram. The shapes of the vector diagrams can strongly affect the compressor performance. A vector diagram is a drawing that uses velocity vectors to relate the absolute fluid velocity, relative fluid velocity and rotating velocity (i.e., the rotational speed of the rotor). It is important to remember that the actual fluid and any particles ingested into the compressor (rain, ice, dirt, etc.) always remain in the absolute velocity even when traveling through the rotor.

The diagram shows that the air flow comes to the IGV with axial direction and velocity $C_{z0.}$ The air then leaves the IGV and approaches the rotor with velocity $C_1$ with blade speed $U_1$ gives the velocity relative to the blade $W_1$ at an angle $\beta_1$ from the axial direction. After passing through the rotor, which increases the absolute velocity of the air, the fluid leaves the rotor with a relative velocity $W_2$ at an angle $\beta_2$ (Fig. 2.5) [3].

C = absolute velocity
$C_u$ = absolute tangential velocity
$C_z$ = axial component of velocity
W = relative velocity
$W_u$ = relative tangential velocity
U = the compressor rotational speed, U=rω
α = absolute air angel
β = relative air angel
0 = the IGV inlet
1 = the IGV exit and the rotor inlet
2 = the rotor exit and the stator inlet
3 = the stator exist
z = the axial component
u = the tangential component

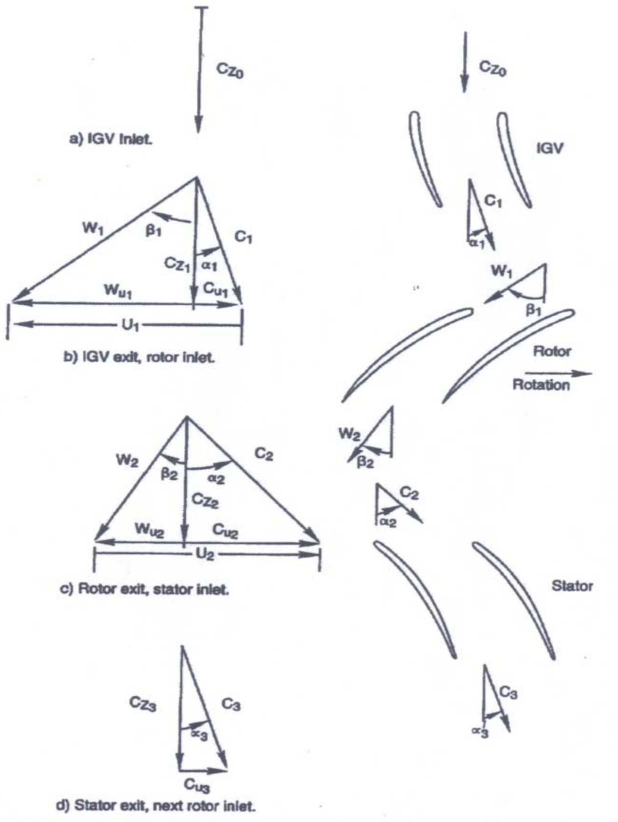

**Figure 2.5 Stage analysis [3]**

## 2.8 Stagnation properties

Considering a steady flow of a fluid through an adiabatic duct as a nozzle (Fig. 2.6) and assuming the fluid experiences little or no change in its elevation and its potential energy. The energy balance relation $(\dot{E}_{in} = \dot{E}_{out})$ for this single stream flow system can be re-write as [1]

$$(h_2 - h_1) + \left( \frac{C_2^2}{2} - \frac{C_1^2}{2} \right) + \underbrace{g(z_2 - z_1)}_{=0} = 0 \tag{2.14}$$

$$h_1 + \frac{C_1^2}{2} = h_2 + \frac{C_2^2}{2} \tag{2.15}$$

Or

$$h_{01} = h_{02}$$

The stagnation enthalpy of a fluid remains constant during a steady-flow process. And any increase in fluid velocity in the nozzle will create an equivalent decrease in the static enthalpy of the fluid. If the fluid were brought to a complete stop, the velocity at state 2 would be zero and the equation (2.15) would become

$$h_1 + \frac{C_1^2}{2} = h_2 = h_{02}$$

$$\Rightarrow h_0 = h + \frac{C^2}{2} \qquad (2.16)$$

Stagnation or total enthalpy is the enthalpy which a gas stream of enthalpy h and velocity C would processes when brought to rest adiabatically and without work transfer. During a stagnation process, the kinetic energy of a fluid is converted to enthalpy (internal energy + flow energy), which results in an increase in the fluid temperature and pressure. The properties of the fluid at the stagnation state are called stagnation properties [1].

When the fluid is a perfect gas, $C_p.T$ can be substituted for h. Thus the stagnation temperature will be

$$T_0 = T + \frac{C^2}{2.C_p} \qquad (2.17)$$

$\frac{C^2}{2.C_p}$ : is the dynamic temperature.

The stagnation pressure will be

$$P_0 = P + \frac{\rho C^2}{2} \qquad (2.18)$$

## 2.9 Gas turbine Configurations

The simple gas turbine cycle consists of three components compressor, combustion chamber and turbine. The possible number of components is not limited to these three components. Other compressors and turbines can be added, with intercoolers between the compressors, and reheat combustion chambers between the turbines. A heat-exchanger which uses some of the energy in the turbine exhausts gas to preheat the air entering the combustion chamber. They may be used to increase the power output and efficiency of the plant. But the expensive of the power plant increase because of added complexity, weight and cost. The gas turbine open cycle can be single shaft and twin shaft arrangements [2].

### 2.9.1 *Open cycle single shaft arrangement*

The open cycle single shift is the most suitable arrangements if the gas turbine is required to operate at a fixed speed and fixed load conditions such as in base-load power generation (Fig. 2.7). The change in load and rotating speed is unimportant in this application. Siemens gas turbine SGT 800 an example of this gas turbine [2].

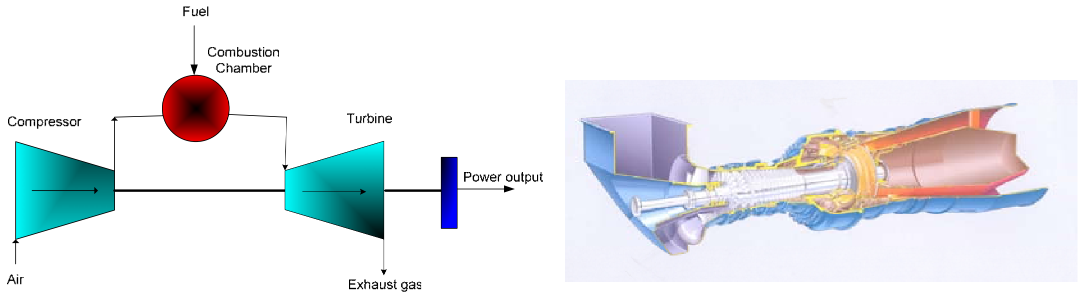

**Figure 2.7 Open cycle single shaft arrangement [85]**

### 2.9.2 *Open cycle twin shaft arrangement*

When flexibility in operation is of paramount importance, e.g. when driving a variable speed load, the use of a mechanically independent (or free) power turbine is desirable (Fig. 2.8). In Twin- shaft arrangement the high pressure turbine drives the compressor and the combination acts as a gas generator for the low pressure power turbine. The turbine runs at the same speed as the compressor, making a gearbox unnecessary. The twin-shaft gas turbine has a significant advantage in ease of starting compared to a single shaft unit, because the starter needs only to be sized to turn over the gas generator. Siemens gas turbine SGT 700 is an example of this arrangement [2].

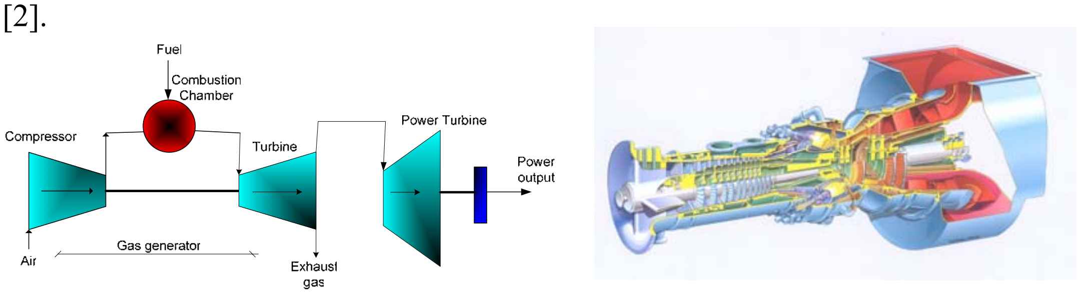

**Figure 2.8 Open cycle twin shaft arrangement [85]**

Variation of power for both single and twin shaft units is obtained by controlling the fuel flow supplied to the combustion chamber.

### 2.9.3 Combined gas and steam cycles

Combined gas and steam cycles are widely used for electric power generation. The combined-cycle unit combines the Rankine (steam turbine) and Brayton (gas turbine) thermodynamic cycles by using heat recovery boilers to capture the energy in the gas turbine exhaust gases for steam production [2]. In the first cycle the fuel is burned and then the combustion mixture expands in the gas turbine to produce electricity. Gas turbine exhaust gas temperature is high sufficient for production of steam, where pure water passes through a series of tubes to capture heat and then boils under high pressure to become superheated steam. The superheated steam leaving the boiler then enters the steam turbine (second cycle), where it powers the steam turbine and connected generator to make electricity. After the steam expands through the turbine it is cooled and condensed back to water in the condenser (Fig. 2.9). By combining both processes the power plant efficiency can be increased [81, 82].

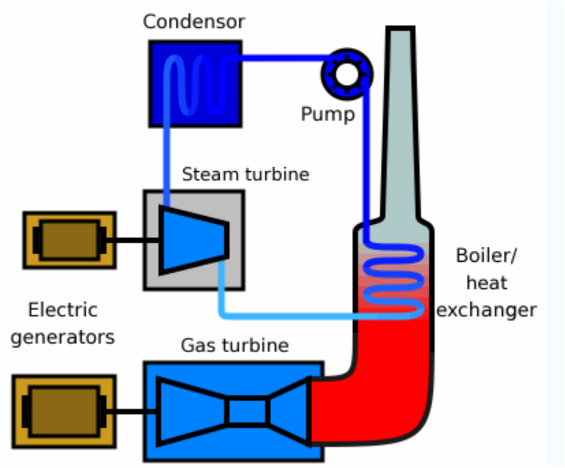

**Figure 2.9 Combined gas and steam cycles [82]**

# 3. Atmospheric properties affecting icing

Stationary gas turbine icing results from the interaction of specific properties such as temperature, moisture and pressure where the temperature and moisture are the most significant.

## 3.1 Temperature

Temperature is a measure of the average speed of molecules. Temperature has a direct relationship with the amount of water vapor the air can hold. The cool temperature holds a small amount of water vapor whereas warm temperature holds large amount of water vapor [6].

## 3.2 Moisture

Moisture is the most important factor in forming clouds and precipitation that together result in icing. Without moisture in form of water vapor there would be no weather or icing. Moisture in the atmosphere develops in the form of ice crystals (solid), water (liquid), or water vapor (gas). Humidity is defined as the amount of water vapor or moisture in the air [6].

## 3.3 Humidity

Humidity is used to measure the amount of water vapour in the air. It can also be used to express the number of molecules of water vapour in a sample of air as a percentage of the total number of molecules of all gases in the sample. The humidity can be subdivided into absolute or relative humidity [44].

## 3.4 Absolute humidity ($\omega$)

Absolute humidity is the ratio of the amount of water vapour ($m_v$) in the air to the amount of dry air ($m_a$) [1].

## 3.5 Relative humidity ($\phi$)

Relative humidity is the ratio of the amount of water vapour actually in the air ($m_v$) compared to the maximum amount of water vapour the air ($m_g$) can hold at that particular pressure. When relative humidity reaches 100 percent, the air is said to be saturated [1].

## 3.6 Saturated air

Saturated air means that the air can no longer hold any additional water in form of vapor. Should any more water vapor be added, or should the air be cooled to a lower temperature, condensation occurs [6].

## 3.7 Dew point temperature ($T_{dp}$)

The dew point temperature is the temperature to which air must be cooled (at constant pressure and constant water vapour content) for saturation to occur, at which the moisture in the air begins to condense. This point is called the saturation point or the dew point. When the dew point is below freezing point, it is commonly referred to as the frost point [1].

## 3.8 Latent heat

Latent heat is energy in the form of heat required to change water from a solid (ice) to a liquid state, and from a liquid to a gas (water vapor) state without any change in temperature. The amount of heat exchanged (absorbed or released) is called the latent heat. When ice melts, heat is absorbed. The heat required must be supplied from the surrounding environment. In the process of freezing water, heat is released to the surrounding environments [6].

## 3.9 Sublimation

Sublimation is defined as the transformation of a solid substance to a vapor state without first passing through the liquid state. That's what happens in the process of frost and ice crystals formation. Water vapor in the air sublimates then directly to ice without going through the liquid stage. The term is also used to describe the reverse process of the gas when changing directly to the solid again upon cooling [6] (Fig. 3.1).

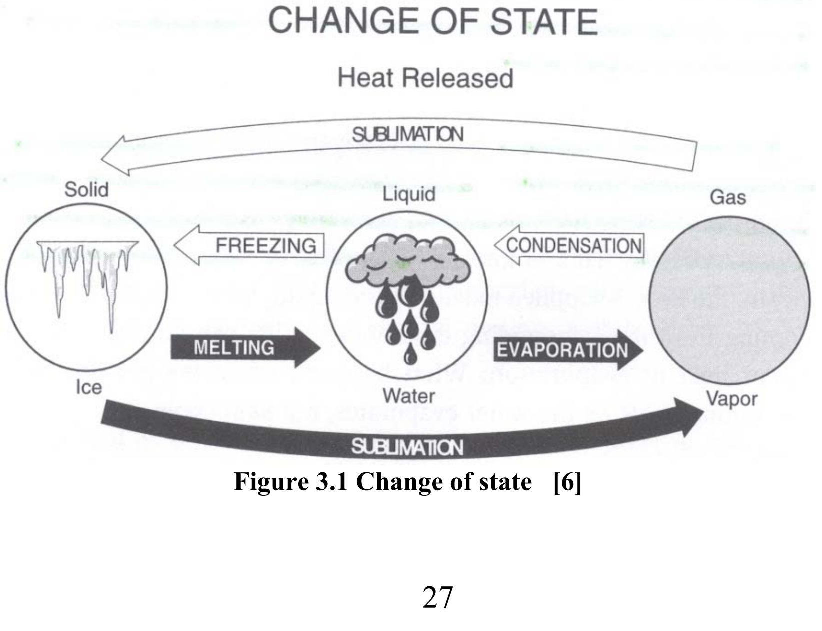

**Figure 3.1 Change of state [6]**

## 3.10 Psychometric chart

The psychometric chart presents the physical and thermal properties of moist air in a graphical form. It shows the relationship between dew point temperature, absolute humidity and relative humidity [43] (Fig. 3.2)

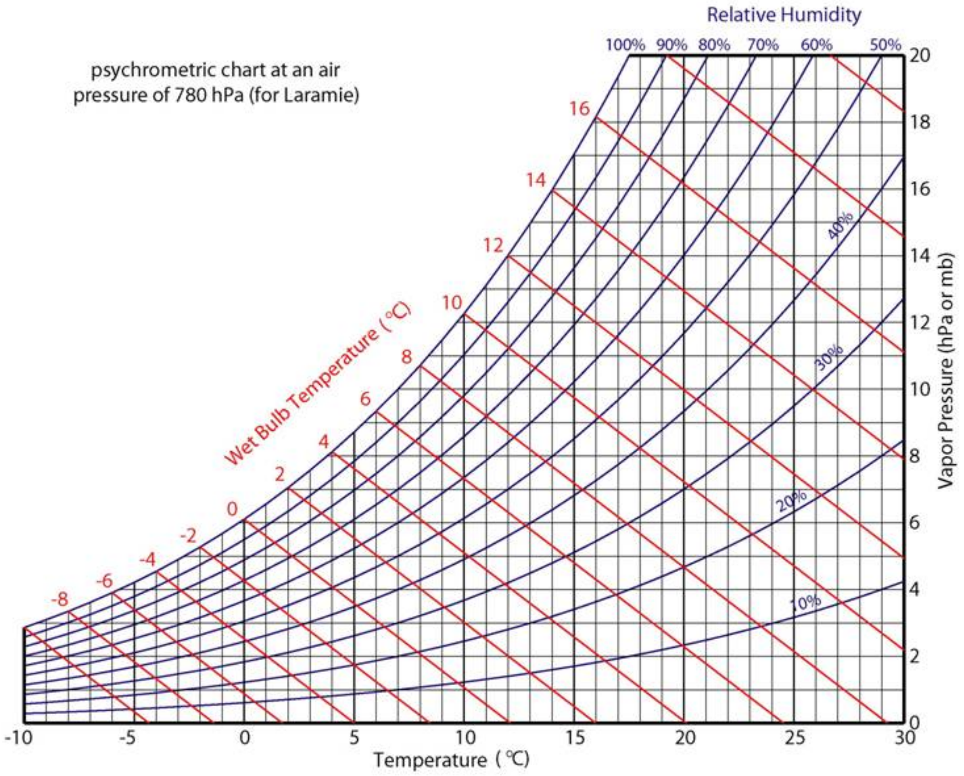

**Figure 3.2 Psychometric chart [83]**

# 4. Introduction to Ice

## 4.1 Introduction

The planet earth, with a thin layer of gas completely covering it, is unique in the solar system. Earth's atmosphere contains about 78 percent nitrogen, 21 percent oxygen and lesser amounts of argon, carbon dioxide, and other gases including water vapour. The lower layer of the atmosphere, the troposphere, contains a bout three quarters of the atmosphere by weight and almost all the water vapour. Nearly all clouds, weather, and icing occur in this layer [6].

## 4.2 Ice types

The icing problem in the gas turbines was investigated a long time ago. Most of this work has been oriented toward the aircraft applications, but many of the data gathered can be translated to the ground based gas turbine power plant. They are two phenomena which can result in the existence of an icing problem in the gas turbine intake. They are Precipitate icing and Condensate icing [36].

### *4.2.1 Precipitate Icing*

The Precipitate icing is used to describe the existence of the free water either in form of liquid or in form of solid in the atmosphere that reach the ground. Precipitate icing can be hail, ice crystals, snow, freezing rain, Ice fog and super cooled water droplets in low level clouds [36].

#### 4.2.1.1 Solid forms

This form of icing generally presents fewer hazards to the gas turbine than does the super cooled liquid precipitation or condensate icing because of the non sticky nature of these types of ice [36]. These precipitation particles will not adhere to cold surface in the inlet system components. Solid forms of precipitate icing include hail, ice crystals, snow, and freezing rain [36].

*Drizzle (Sometimes popularly called mist)* is very small, numerous, and uniformly distributed water drops with diameters less than 0.5 millimetres. Unlike fog droplets, drizzle falls to the ground. It usually falls from low stratus clouds and is frequently accompanied by low visibility [58, 59].

*Freezing rain and freezing drizzle* are caused by liquid precipitation falling from warm air into air that is at or below freezing. Droplets freeze with impact a cold ground or other exposed surfaces [55].

*Ice* crystals *(They also called diamond dust)* are seemed to be suspended in the air. They are very tiny small particles of ice. They form when the temperature is so low colder than -30 [C$^o$]. They are the beginning of many other precipitates like ice fog and hail [46, 59].

*Ice fog* is fog composed of ice crystals instead of water droplets in saturated air. In the ice fog situation the temperature is becoming too cold for any supercooled water to occur. It exists when water vapour sublimates directly into ice crystals. It forms in very low temperatures colder than -30 C$^o$ [58].

*Snow is* composed of white or translucent ice crystals, chiefly in complex branched hexagonal form and often integrated into snowflakes. Snow occurs in meteorological conditions similar to those in which rain occurs, with exception for initial temperature that must be at or below freezing point [59].

*Hail* is precipitation in the form of balls or irregular lumps of ice. There diameter ranging from diameters between 5 and 50 mm. Hail is composed either of clear ice or of alternating clear and opaque snowflake layers. Hail is associated with thunderstorm activity [63].

The installation of snow hoods over the entry to the intake system causes the intake air stream to flow vertically upwards as it enters the system. The velocity in the snow hoods is low hence large particles with high settling rates such as hail cannot enter the intake system because of the effect of inertia forces [36]. Other particles which are smaller like the drizzles can be removed by filter elements.

#### 4.2.1.2 Liquid form

The condensed water suspended in the air stream and liquid precipitation can remain liquid even when the air temperature is below freezing [6]. This occurs because the liquid needs a surface to freezing upon. The liquid droplets will freeze without a nuclei surface if the temperature drops low enough. As a general rule, liquid cloud or precipitation droplets between freezing 0 C$^o$ and -15 C$^o$ will remain liquid. When the temperature drops to below -30 C$^o$, all liquid droplets will solidify [54]. Droplets that are liquid and are below freezing referred to as supercooled droplets. The extent to which supercooling is possible depends upon the size o f the droplets, the smaller the droplets, the lowest the temperature needed to convert the droplets to ice[52]. In clear air, in which there are no dust particles to trigger the phase change, droplets are reported to turn into ice at -15 C$^o$ to -20 C$^o$ for a diameter of 1 mm, at -30 C$^o$ for 10-20 μm and -40 C$^o$ for the smallest diameter [34]. Supercooled water droplets can constitute a hazard when they ingest in the inlet system. They can adhere to the surface causing a big risk for ice formation on it. When supercooled water droplets strike over a surface they begin to freeze. The lower the air temperature and the colder the surface is, the greater the fraction of the droplet that freezes immediately on impact. Similarly, the smaller the droplet is, the greater the freezing droplet fraction immediately on impact becomes. Generally the maximum potential for icing occurs with large droplets at temperature just below 0 C$^o$ [54].

### 4.2.2 Condensate icing

The condensate icing does not exist as an atmospheric condition but it is a situation that exists in the gas turbine under certain atmospheric conditions. It exist when the air stream accelerate in the intake system (bellmouth) to high velocity. This results in a static temperature depression in order of 15 C$^o$ or even more than this depending on the air velocity. In such conditions the air will be saturated and the water vapour will condense from the air to the surface of the intake system. If the surface temperature is below the dew point temperature of the static air in the inlet and below the freezing point temperature, the ice will be formed on the surface [31]. This type of icing constitutes hazards on the compressor because it adheres on the surface. The ice types can be rime ice, glaze ice or frost [36, 78].

#### 4.2.2.1 Rime ice

Rime is formed from small supercooled fog droplets when they strike over a surface at temperatures at or below frost point. Since the droplets are small, water droplets freeze rapidly before the drops have time to spread over the surface. Each droplet has a chance to freeze completely before another droplet hits the same place [54]. Thus the amount of water remaining after the initial freezing is insufficient to runback and creates a liquid layer on the surface. This is called the dry growth of the ice [12]. The ice contains a high proportion of trapped air, giving it its white appearance. Rime ice is milky and less dense than glaze ice, clings less tenaciously and has low adhesive properties. It is brittle and easier to remove than glaze ice [54, 45] (Fig. 4.1)

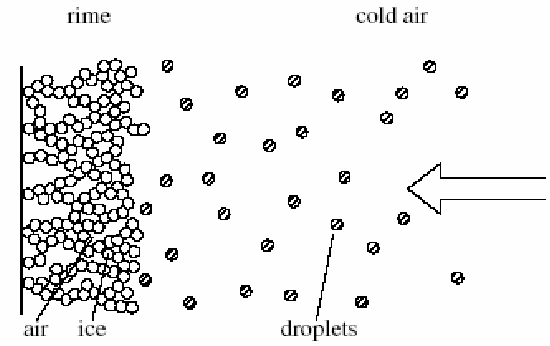

**Figure 4.1 Rime ice [12]**

Rime ice is most frequently encountered in stratiform clouds at low temperature -20 [C$^o$] but there is still a risk of rime ice at temperature below -30 [C$^o$] [6, 47]. The factors favoring the formation of rime ice are small drop size, a high degree of super cooling, and rapid dissipation of latent heat of fusion [47].

#### 4.2.2.2 Glaze ice

Glaze ice *(called also clear ice)* is formed from large supercooled fog droplets when they strike over a surface at temperatures at or below frost point. It exits when the droplets does not freeze completely before additional droplets become deposited on the first one. Freezing of each drop will be relatively gradual, due to the latent heat released in the freezing process, allowing part of the water drop to flow rearwards before it solidifies [54]. The slower the freezing process, the greater the flow-back of the water before it freezes. This is called the wet growth of the ice [12]. In this process a liquid layer on the surface of the accretion forms and freezing takes place beneath this. The flow-back is greatest at temperatures between 0 [C$^o$] and -15 [C$^o$] [6, 47]. Glaze ice is mostly clear and smooth. Glaze ice tends to range from transparent to a very opaque layer. It's denser, harder and more transparent than rime ice and it looks like ice cubes [54, 45] (Fig. 4.2)

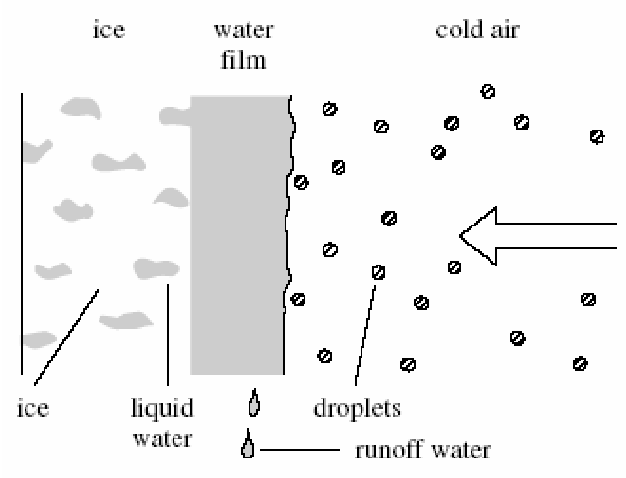

**Figure 4.2 Glaze ice [12]**

It has high density that makes it difficult to be removed. Factors favoring formation of glaze ice are large droplet size, slight super cooling, and slow dissipation of the latent heat of fusion. Glaze ice is usually not as widespread as rime [47].

### 4.2.2.3 Frost

Frost is the fuzzy layer of ice crystals on a cold object. It resembles snow but is the result of deposition of water vapor in saturated air [10, 58]. Frost is ice that sublimates directly on the surfaces on which it is in contact with. Sublimation occurs when water vapor goes directly from the vaporous state to the solid state. This happens when the solid surface temperature is less than the frost point temperature [45]. Factor favoring the formation of frost is very low temperature of air and surface temperature below freezing point [10]. Depending upon the actual values of ambient-air temperature, dew point, and the temperature attained by surface objects, frost may occur in a variety of forms. These include hoarfrost (or white frost), and dry freeze (or black frost) [58]. The frost can lead to increasing in pressure drop. The frost can constitute hazard when its melts and freezes again to form glaze ice. This process is called melting freezing process [10].

#### 4.2.2.4 Hoarfrost

Hoarfrost is deposit of interlocking ice crystals formed by direct deposition on objects. The deposition of hoarfrost is similar to the process by which dew is formed, except that the temperature of the befrosted object must be below freezing. It forms when air with a dew point below freezing is brought to saturation by cooling [58]. Rime ice look like hoar frost but rime ice is formed by vapor first condensing to liquid droplets and then attaching to the surface, while hoar frost is formed by direct sublimation from water vapor to solid ice. They are two features of hoarfrost as compared with other precipitate icing forms [45]. *First* is because hoarfrost implies a thermodynamically unstable condition in the air (the air is saturated); the frost will accumulate on the first disturbing surface. It has been observed that frost accretions accumulate on the filter elements. *Second* is the hoarfrost accretion form which is usually sugary rime ice with a high percentage of included air. This ice formation is easy to remove [49]. The primary danger to gas turbine operation in hoarfrost conditions is the rapid increase in pressure drop in the intake system with the high blockage rates.

## 4.3 Collection efficiency (Ice accretion)

The collection efficiency can be defined as the fraction of liquid water droplets that actually strike the surface and intercepted on it to the number of droplets coming across the surface path. There are various aerodynamics factors that affect the collection efficiency of the surface, surface temperature, liquid water content, radius of curvature (airfoil shape), the velocity of the air stream and the droplet size [54,40,41].

### *4.3.1 Surface temperature*

Ice can build up in different places and take different shapes depending on the surface temperature. Temperature influences on ice accretions has been studied in both condensate icing and precipitate icing.

#### 4.3.1.1 Condensate ice

1. Ice formation at, or just below freezing point:

Between 0 $C^o$ and -3 $C^o$ ice will form on the leading edge of the blades from the blade root towards the tip covering a bout 70%. The reaming 30% of the blade at the tip is free of ice due to kinetic heating (Fig. 4.3). If the blade ice is allowed to build up, the maximum accretion point will be the mid-point of this area [53].

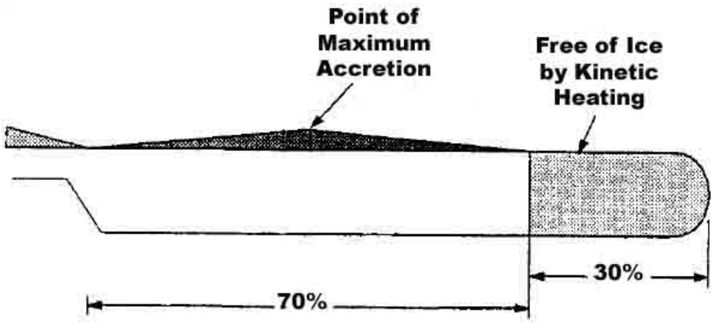

Figure 4.3 Ice formations at, or just below freezing point [53]

2. Ice formation at temperature between -3 C$^o$ and -15 C$^o$:

It has been shown that at -3 C$^o$ about 70% of the blade will be covered by ice. When the temperature decreases, ice deposits further along the blade until 100% coverage from root to tip takes place (Fig. 4.4). The lower temperature of the air has overcome the kinetic heating. The maximum accretion point is still the midpoint of the area [53].

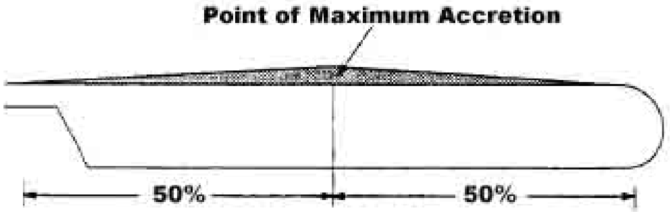

Figure 4.4 Ice formations at temperature between -3 C$^o$ and -15 C$^o$ [53]

### 4.3.1.2 Precipitate icing

1. Leading edge ice formation at temperature above -15 C$^o$

The ice formation on the leading edge of the blades at a temperature above -15 [C$^o$] will take a form of glaze ice. The ice build-up at point B is heavier than at stagnation point A because only the freezing fraction, which is the smallest part of the super cooled droplet, freezes on impact. The remaining ice will runs back towards point B and freezes between B and C (Fig. 4.5) [53].

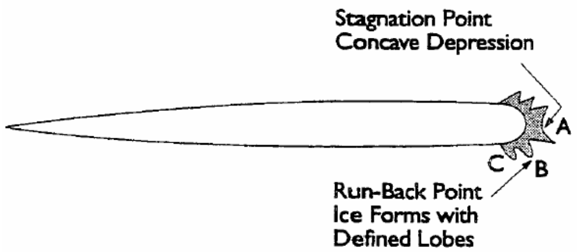

Figure 4.5 Leading edge ice formations at temperature above -15 C$^o$ [53]

2. Leading edge ice formation at temperature below -15 C$^o$

At temperature below -15 C$^o$, ice forms on the leading edge in a different way; the ice formation is more symmetrical. This is because the freezing fraction of the super cooled droplet is much larger with very little run-back (Fig. 4.6). Thus the rime ice will be the result [53].

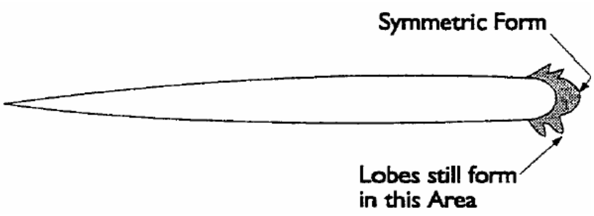

**Figure 4.6 Leading edge ice formations at temperature below -15 C$^{o}$ [53]**

### *4.3.2 Liquid water content*

Liquid water content varies with temperature. LWC is important in determining how much water is available for icing but is very difficult to quantity because it is not measured routinely [56]. At low temperature the number of frozen droplets increases considerably, while at the same temperature, the liquid content falls. The liquid water content is low at temperature below 25 C$^{o}$ and generally disappears at minus 40 C$^{o}$ (Fig. 4.7). The liquid water content of a cloud also varies over time [54].

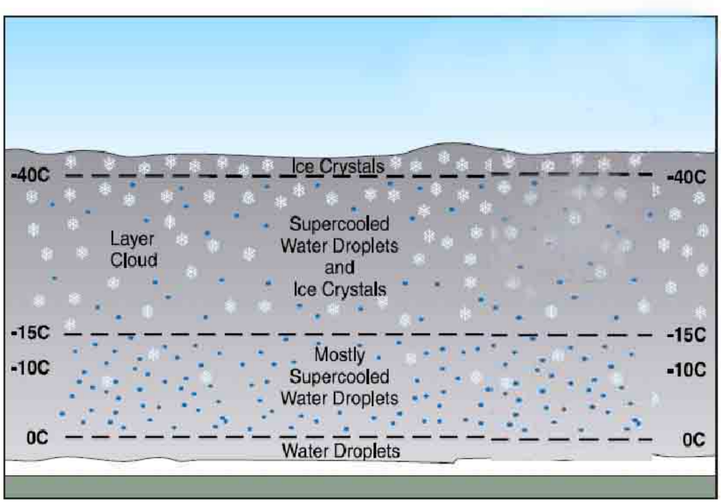

**Figure 4.7 Liquid water content varies with temperature [54]**

### *4.3.3 Radius of curvature*

Radius of curvature with big radius of curvature disrupts the air flow causing the smaller super cooled droplets to be carried around the blade by the air stream. Since the boundary layer that surrounds the blade is deeper and most of the super cooled water droplets that penetrate this layer are centrifuged off, only a small proportion form ice on the blade see (Fig. 4.8) [53].

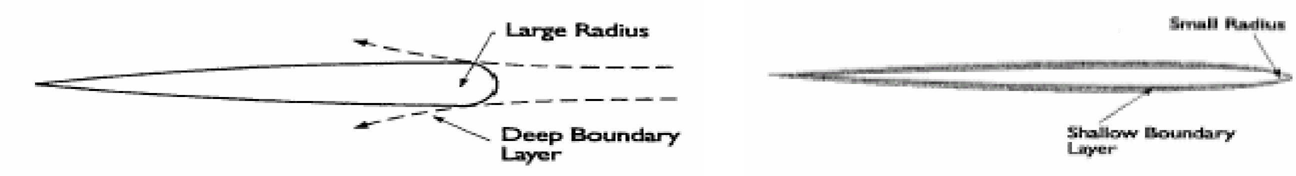

**Figure 4.8 Radius of curvature [53]**

For this reason, large thick blades collect ice less efficiency than thin blades (Fig. 4.9) [54].

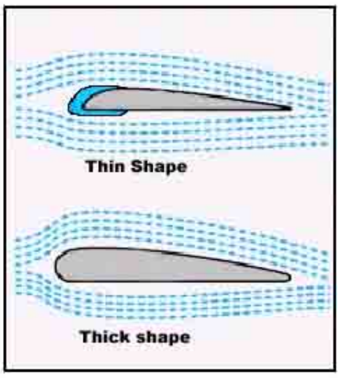

**Figure 4.9 Collection efficiency as function of radius of curvature [54]**

### 4.3.4 Velocity of air stream

Velocity of air stream the higher the velocity of the air stream the less chance the droplets have to be diverting around the blade and they will collide with blades (Fig 4.10) [54].

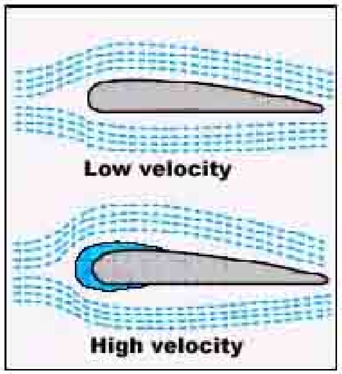

**Figure 4.10 Collection efficiency as function of velocity of the air stream [54]**

### 4.3.5 Droplet size

Droplet size the larger the droplet the more difficult it’s for the air stream to displace it. Because of the inertia effect and weight of the droplet it can’t follow the air stream and it continues in its way and hit the surface (Fig. 4.11) [52, 54, 51].

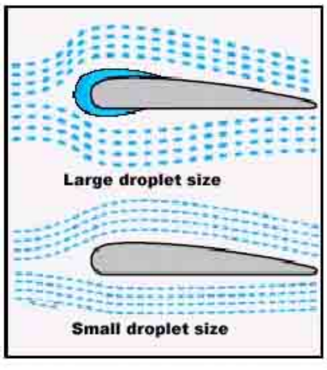

**Figure 4.11 Collection efficiency as function of droplet size [54]**

## 4.4 Ice accretion process

During ice accretion processes, roughness develops on ice covered surfaces. The roughness affects the convective heat transfer and the droplet collection efficiency, which in turn controls the ice shape [11]. For rime ice grown at cold temperature the impinging droplets freeze on impact and form beads. After that new impinging droplets impact near other droplets to form growing beads. Growth ends when a maximum height is reached (Fig. 4.12) [13].

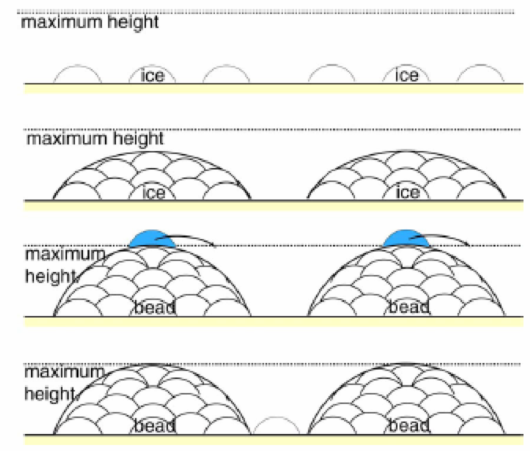

**Figure 4.12 Rime ice accretions [13]**

The roughness height is at a maximum at the stagnation point and decreases towards ice end. The solidification time is in the order of a millisecond (Fig. 4.13) [13]

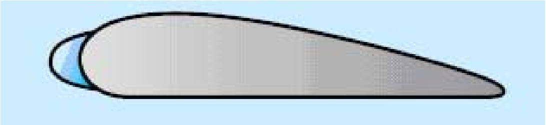

**Figure 4.13 Rime ice shape [47]**

For glaze ice formed at warmer temperature than rime temperature, the ice surface is composed of a smooth zone near the stagnation point, and beads formed at the transition between the smooth and rough surface. The beads grow being partially frozen and partially liquid. When the beads reach a maximum height, the liquid part runs back due to the aerodynamic force, a fraction of which remains trapped in the gap between the frozen parts of the beads, while the rest flows and becomes runback water (Fig. 4.14) [13].

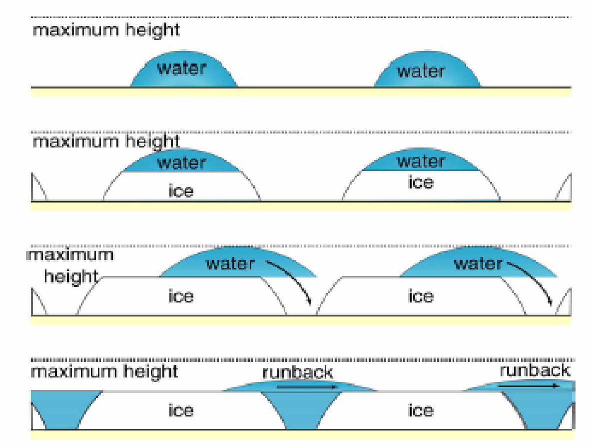

**Figure 4.14 Glaze ice accretions [13]**

The roughness height is at a minimum at the stagnation point, this value increases rapidly to reach a maximum, after which it decreases towards the ice end (Fig. 4.15) [13].

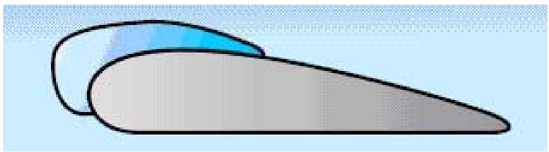

**Figure 4.15 Glaze ice shape [47]**

## 4.5 Condensation process and super saturation

Conventionally the saturation (or equilibrium) vapour pressure for a water surface is defined with respect to a flat surface of pure water. In this case the saturation vapour pressure is a function of temperature only. But in reality the vapour pressure for a water surface is not only function of temperature but also of the surface tension [49]. Highly curved water surfaces have higher equilibrium vapour pressures than flat water surfaces. This is according to Laplace formula which describes the condition of mechanical equilibrium [50]

$$P_i - P_o = \frac{2.\sigma_v}{a}$$

$\sigma_v$ **:** The surface tension [N/m]

a: The droplet radius [cm]

The surface tension is responsible of the shape of liquid droplets. In small droplets the surface tension between liquid molecules are large since the molecules do not have other like molecules on all sides of them. Thus they cohere more strongly to molecules directly associated with them. The tendency to minimize that tension pulls the droplet into spherical shape with high curved surface. The smaller a sphere is the greater its curvature (Fig. 4.16) [61, 64].

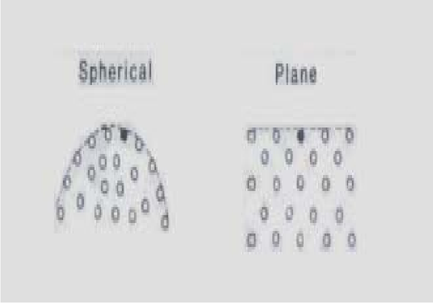

**Figure 4.16 Surface tension [50]**

From Laplace formula we can conclude that the pressure inside the droplet (vapour pressure) is inversely proportional to the droplet radius. Therefore with decreasing radius, of water molecules favours the escape from the droplet and resist the return to a molecule from the vapour phase. As a conclusion we can say at the initial condensation results in liquid droplets of very small diameter and thus large curvature.

## 4.6 Clouds

A cloud is a visible mass of minute water droplets (or ice particles) suspended in the atmosphere. Clouds initially form as the atmosphere becomes saturated with respect to liquid [56]. It differs from fog in that it does not reach the surface of the earth. Icing clouds can be divided into two general categories stratiform and cumuliform [47].

*Stratiform* describes clouds of extensive horizontal development, associated with a stable air mass and they are thick and grey (Fig. 4.17) [48]. They are classified as low clouds [60].Stratiform clouds consist of small water droplets. Icing conditions can prevail for horizontal extents up to 200 miles. Stratiform clouds consist of moderate LWC (Liquid water content) which can produce rime icing. The most likely altitude for stratiform cloud icing is only 5000 ft (1524 m).They form when a layer of air cools down below its dew point (the temperature at which condensation begins). An example of stratiform clouds is fog, which is simply ground level stratiform cloud [36].

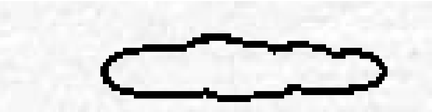

**Figure 4.17 Stratiform clouds [60]**

*Cumuliform* describes clouds that are characterized by vertical development in the form mounds [6]. It's associated with an unstable air mass [48]. They are classified as clouds with vertical development (Fig. 4.18) [60]. Because of upward moving currents, cumuliform clouds can support large water droplets. Icing conditions extends horizontally for only 3 to 6 miles. Cumuliform clouds consist of large liquid water content. The most likely altitude for cumuliform cloud icing is 10000 ft (30418 m) [36].

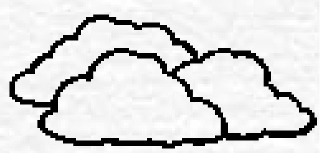

**Figure 4.18 Cumuliform clouds [60]**

# 5. Icing mechanism

## 5.1 Physics of ice

The possibility of condensate ice on the surfaces of the inlet bellmouth or inlet guide vanes of gas turbine depends upon combination of various factors, ambient temperature, ambient relative humidity, air stream velocity and surface temperature [31,40]. Icing can occur in the inlet system by at least two mechanisms, *condensate icing* and *precipitate icing* [36]. Precipitate icing doesn't constitute real hazard in the inlet system because of the installation of the inlet hood and filter system in the inlet of the intake system which hinder ingestion of precipitate ice to the compressor [36]. The only hazard precipitate icing can constitute is due to super cooled water droplets. Super cooled water droplets adhere quickly to the surface and build ice. It is complicated to predict the trajectories of the water droplets in the inlet system. Thus it's difficult to predict the ice formation on the surface as a result of super cooled water droplets [37]. With concern to condensate icing it is known that icing possibility generally increases with decreasing cross-section area. This can be explained as follows; the ambient air enters the intake system of the gas turbine with velocity around 5 m/s. When the air stream reaches the bellmouth, which is a converging section, the cross-section area will decrease and the air stream will accelerate according to fluid dynamics laws, to high velocity in range between 150-270 [m/s] with a subsonic Mach number [1].
The properties of subsonic nozzle can be obtained by deriving the mass balance equation for steady-flow process [1]:

$$\dot{m} = \rho . A . V = \text{ Constant} \qquad (5.1)$$

We get in the end the following equations:

$$\Rightarrow \frac{dA}{A} = \frac{dp}{\rho V^2}(1 - M^2) \qquad (5.2)$$

$$\Rightarrow \frac{dA}{A} = -\frac{dV}{V}(1 - M^2) \qquad (5.3)$$

In the subsonic nozzle $M<1$
$\Rightarrow (1-M^2)$ is positive.
A very important conclusion can be taken from equation (5.2) and (5.3). The static pressure decreases and the velocity of the air increases as well as a result of decreasing cross-section area of the converging nozzle (Fig. 5.1) [1].

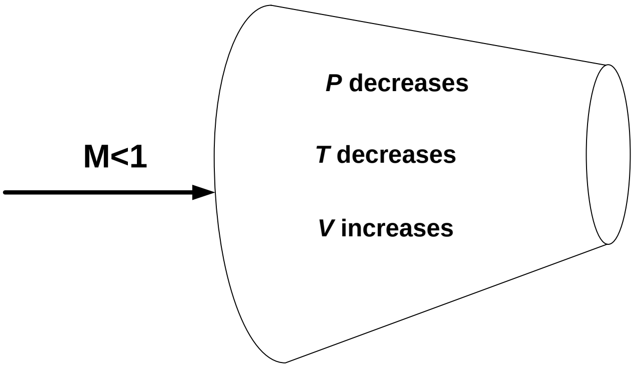

**Figure 5.1 Subsonic nozzle**

The relation between temperature and pressure with Mach number can be given for the following equations [1].

$$\frac{T_o}{T} = 1 + \frac{k-1}{2}M^2$$
$$\frac{P_o}{P} = 1 + (\frac{k-1}{2}M^2)^{\frac{k}{k-1}} \quad (5.4)$$

From these equations it's apparent that with increasing air velocity in the converging nozzle, the static temperature and the static pressure will decrease [1]. With decreasing static temperature of the air, the maximum water vapour capacity of the air will also decrease. After a while the maximum capacity of the air will be equal to its water vapour contents. When that happens we say that the air becomes saturated and this is called the saturation point or dew point [1]. If the surface temperature of the inlet system is lower than the dew point temperature of the air in the inlet system the water vapour in the air will begin to condense on the surface (Fig. 5.2). If it coincides that the surface temperature at or below the freezing point temperature, ice begins to build on the surface [31, 32]. The surface temperature can be calculated with help of the *Recovery Factor* see 6.1

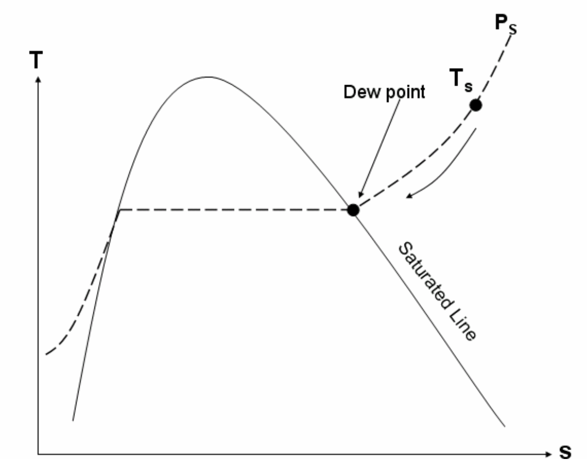

**Figure 5.2 Dew point temperature**

## 5.2 Recovery factor

### *5.2.1 Physical mechanism*

When a fluid flows through a pipe having an insulated wall, the temperature at the wall ($T_{wa}$) is neither the stagnation temperature ($T_0$) nor the static temperature ($T_s$) of the stream. In a gas flow the wall temperature usually lies between stagnation and static temperature. In case of a high-speed gas stream, the factors influencing ($T_{wa}$) is controlled by complex phenomena in the boundary layer [4]. If we consider the high-speed gas stream flow next to insulated wall, the velocity gradient will be as shown in (Fig. 5.3) as a result of the viscous effects. The region, where the velocity increases rapidly and approaches the velocity of the free flow velocity of the main stream, is called the boundary layer [4].

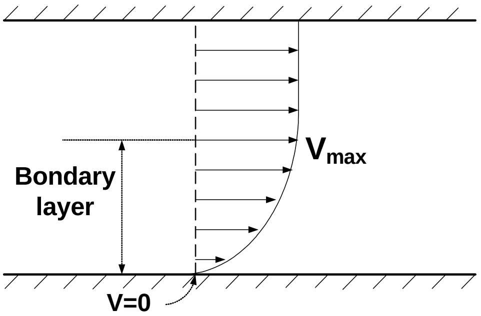

**Figure 5.3 The boundary layer**

The outer layer of the fluid does viscous work with the wall where the velocity is zero and the viscous stresses is highest. The viscous stresses within the boundary layer do shearing work on fluid particles and consequently, the internal energy and temperature of the fluid in the inner layers tend to rise. Since the wall is insulated the inner layer and the wall would become progressively hotter. The temperature gradients created by the viscous shearing work lead to a conduction of heat away from the wall thus tending to limit the temperature rise of the wall. After these effects have been brought into balance everywhere in the fluid, the temperature distribution in the boundary layer is then being as shown in (Fig. 5.4) [5]. The wall temperature is greater than free flow temperature ($T_s$) and less than stagnation temperature ($T_0$).

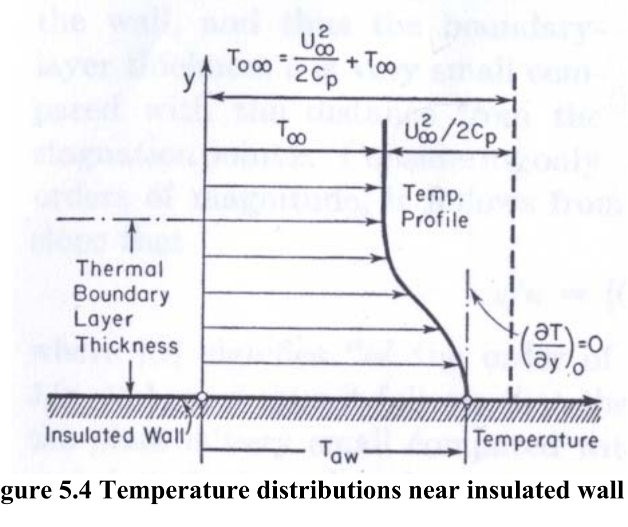

**Figure 5.4 Temperature distributions near insulated wall [5]**

## 5.2.2 Flat plate

Heat transfer to the surface of an object exposed to a high velocity flow depends on the shape of this object as well on the flow field to which it is exposed. One geometry, which has been investigated in detail because it can be treated theoretically in a sample, is a flat plate. The flat plate defined here as a situation where a plane surface is exposed to a one dimensional flow. The magnitude of ($T_{wa}$) relative to the values of ($T_s$) and ($T_0$) is usually expressed by the recovery factor RF [7, 8].

$$RF = \frac{T_{wa} - T_s}{T_0 - T_s} = \frac{T_{wa} - T_s}{V^2 / 2cp} \qquad (5.5)$$

$$RF = \frac{\frac{T_{wa}}{T} - 1}{V^2 / 2cp} = \frac{\frac{T_{wa}}{T} - 1}{\frac{k-1}{2} M^2}$$

## 5.2.3 The experimental relation for the recovery factor

The experimental relation of the recovery factor is

Laminar flow $RF = \sqrt{Pr}$ → RF=0.85

Turbulent flow $RF = \sqrt[3]{Pr}$ → RF=0.87-0.9

Where air at normal temperature has a Prandtl Number of 0.72 [7, 8].

The measurements in the insulated tube, with subsonic speed (Mach number ranging from about 0.3 to 1.0) and turbulent flow indicate that the recovery factor is in range between 0.87 and 0.91 (Fig 5.5) [5]. This is generally in agreement with measurements of turbulent recovery factors on flat plates.

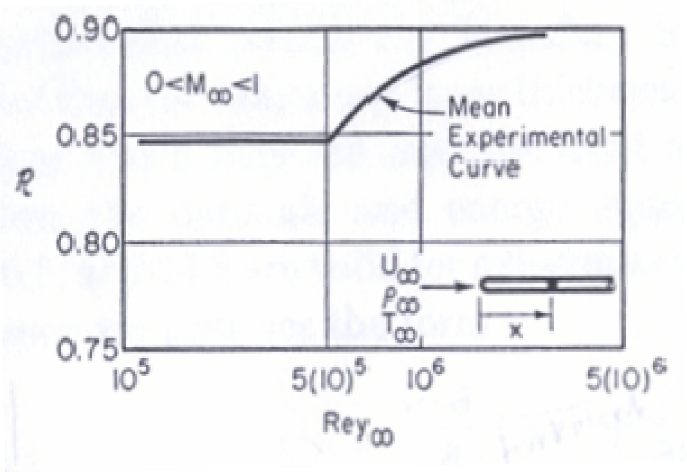

**Figure 5.5 The measurement recovery factor [5]**

## 5.3 Ice place prediction

While the physics of ice formation are particularly complex, it is difficult to predict precisely where condensate ice will build up first in the intake system. As we see from the explanation of icing mechanism the ice possibility increases with increasing air stream velocity which coincides with decreasing cross-section area. Theory tells us that at the stagnation point the air temperature is highest, ie the same as the air total temperature, and around the body the static temperature of air is less. The point where freezing takes place lies between the stagnation point and the point (A) where the velocity will increase as a result of decreasing cross-section area (Fig. 5.6) [30].

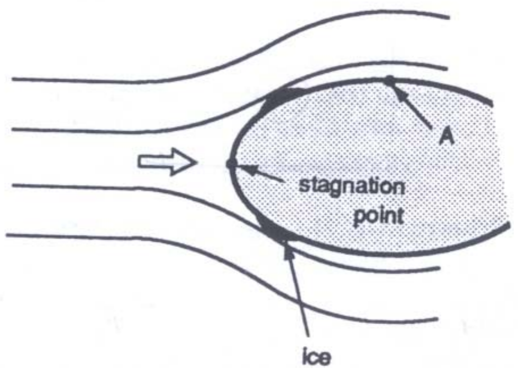

**Figure 5.6 Ice place [30]**

However it will be found out in section 9 that the assumption is only correct up to a certain air stream velocity. A very high air velocity leads to a large temperature drop in the inlet system. The temperature depression depends upon operation conditions and the gas turbine design. From this follows that the static temperature in the inlet system will be, at or below -30 [$C^o$]. In these conditions the water droplets in the air will crystallize to solid forming *ice crystals* or/and *ice fog*. In other words the water condensation from the air takes place below specific velocities. Depending on their relative location in the inlet system and atmospheric conditions condensate and/or precipitate icing can build up on different places in the inlet system, $IGV_s$, bellmouth, struts, plenum chamber and filter elements [32]. It was found that the largest possibility of condensate ice to build up is on the $IGV_s$ that will be explained in the next section. The ice accumulation in the inlet system components is investigated from the first component in the system to the compressor as presents below.

## 5.4 Ice places in the gas turbine

*Inlet hoods* are not likely to accrete ice under any environmental conditions. The installation of inlet hoods over the entry to the intake system causes the inlet air stream to flow vertically upwards as it enters the system. Velocity in inlet hoods is low; hence large particles with high settling rates cannot be entrained to the intake system. Such particles include hail, freezing rain and snow [36].

*Filter elements* can rapidly plug under almost all icing conditions. Frost is the most likely ice type that can accumulate on the filter elements [36]. The water droplets in the air are in unstable situation. So ice will build up on first obstacle coming in the water droplets path. Ice accretion on the filter elements increase pressure drop which leads to performance loss.

*Silencer elements* are usually in very low velocity areas downstream of the filter elements. Condensate icing is not problem in these low velocity regions. Precipitate ice which can reach these components depends greatly on the type and effectiveness of the components in the intake of the system. If the intake system is equipped with inlet hoods and a static filter system, there will be a very little risk of any precipitate ice to reach the silencers elements [36].

*Plenum* is the lower part of the inlet system [9]. A typical stationary gas turbine installation places the gas turbine intake inside a plenum chamber. Plenum provides a structure for the protective intake components and contains the compressor noise. Condensate icing is, generally, not a problem in the plenum because air velocities are too low for a significant static temperature depression. Exceptions to this generalization are high-velocity vortices which have been observed near the bellmouth. Thus the plenum enclosure should be large to reduce air stream velocities approaching the bell mouth. The plenum floor is the only likely place for ice formation. This region can be susceptible to *leakage icing*. Leakage icing means formation of ice on the plenum floor will be as a result of melting water dripping onto this region from the roof. The ice, which may form on the plenum floor, can be glaze ice as well as frost. The ice formation on the plenum walls is harmless as long as the horizontal distance to the compressor intake is great enough to prevent ingestion of ice [36].

*Bellmouth* very important feature is to deliver the air to the compressor in a uniform way [9]. Because of the bellmouth has a conversion shape, the velocity of the air steam in the inlet system begins to accelerate when it enters the bellmouth. The velocity of the air stream increases to high values which leads to a great temperature depression in the inlet system. Condensate icing can be the result on the bellmouth surface. The precipitate icing doesn't constitute any hazard in the bellmouth because of inlet system components hinders precipitate ice to approach this region.

*Struts* have a large airfoil cross-section with moderate ice accretion efficiency [36]. Condensate icing is the primary icing hazards in this region. Because of the large surface of the struts the runback icing, if it takes place, leads to building glaze ice on the strut surface. Ice on the struts surface may be sizeable and present a considerable problem. This type of icing may be caused by heating from service pipes placed inside the struts, e.g. oil feed and oil lines [36]. Heating can increase ice temperature which slows icing process. Thus give enough time for water to runback over the struts creating water film before it crystallizes to ice.

*IGVs* have a task to direct the air flow onto the first stage compressor rotor. The surface of the IGVs is small and they have a thin shape. Thus their ice accretion efficiency is high [36]. Condensate icing is the icing that constitutes hazard on the compressor. The velocity in which condensate icing is likely to take place coincides with the velocity in the IGVs (Fig. 5.7). Both glaze ice and rime ice can form on the IGVs.

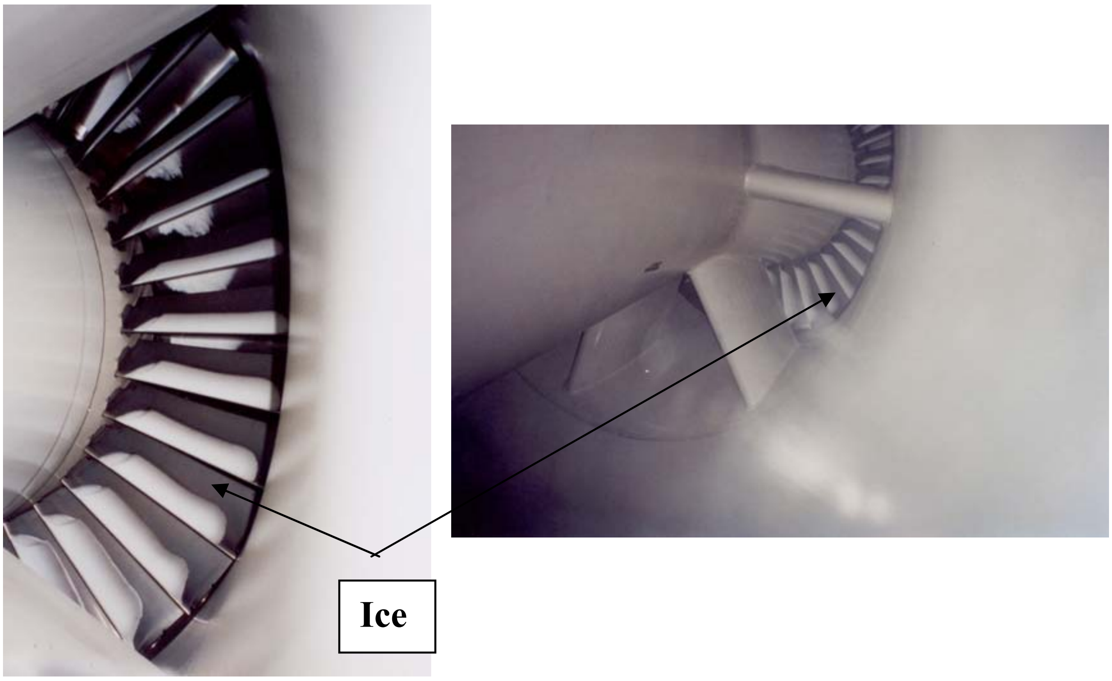

**Figure 5.7 Ice formations on IGVs [85]**

*First stage compressor*: icing conditions experienced by first stage compressor rotor blades are less severe than other places in the intake system. The reasons for this can be that ice had been formed and collected on the inlet components. Another reason can be that ice formation on the compressor blades are subjected to centrifugal and aerodynamic forces which will induce periodic shedding [36].

*Remainder compressor stages*: after the first stage of the compressor, the temperature and the pressure increase rapidly as a result of compression effect. Therefore there will not be problem of icing.

The (Fig. 5.8) presents the inlet system of the compressor and in which components ice can formed as a result of both condensate and precipitate icing.

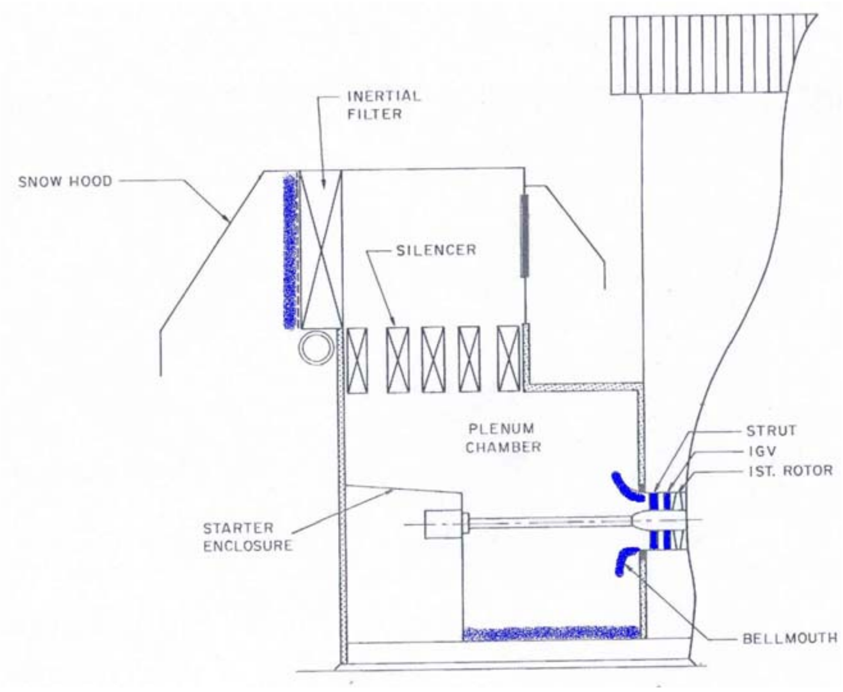

**Figure 5.8 Ice places in gas turbine [36]**

## 5.5 Ice accumulation tendencies in intake system

The ice accumulation tendency in the inlet system is demonstrated in table 5.1. The table shows the most likely ice types that can form on the inlet components. It's perceptible that precipitate icing accumulates on the first components in the inlet system and doesn't reach the inlet of the compressor. Condensate icing occurs where the air velocity is high at, struts, bellmouth and IGVs. Clearly since the local conditions and geometry are different from installation to another it is difficult to generalize where ice will initially from. Each installation must be judged on its own.

| Section No | Intake Components | Precipitate Icing | | | | Condensate Icing | | |
|---|---|---|---|---|---|---|---|---|
| | | Hail*<br>▲ | Ice Crystals<br>◬ | Snow<br>✱ | Freezing rain<br>●∽ | Hoarfrost<br>⊔ | Rime Ice<br>V | Glaze Ice<br>⩝ |
| 1 | Inlet Hoods | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 2 | Filters | 1 | 2 | 2 | 1 | 4 | 2 | 2 |
| 3 | Plenum Chamber | 1 | 1 | 1 | 1 | 2 | 2 | 2 |
| 4 | Bellmouth | 1 | 1 | 1 | 1 | 4 | 4 | 3 |
| 5 | Struts | 1 | 1 | 1 | 1 | 4 | 4 | 3 |
| 6 | Inlet Guide Vanes (IGV$_s$) | 1 | 1 | 1 | 1 | 4 | 4 | 3 |
| 7 | First Stage Compressor | 1 | 1 | 1 | 1 | 2 | 2 | 2 |

**Table 5.1 Ice accumulation tendencies in intake system [* 57]**

Possibility:
1. None
2. Small
3. Moderate
4. Strong

# 6. Inlet air effect on gas turbines

## 6.1 Introduction

Gas turbines operate in virtually all types of environments; from the hot sandy areas of the Sahara desert, to the freezing, moist, snow arctic climate. The gas turbine ingests huge amount of air every second during its operation. The air carries a mixture of contaminants varying in size, type and concentration depending on the environment. There are five different environments that are considered during the study of containments' influence on the gas turbine. These are the desert, tropical, industrial, offshore marine and the arctic environment [21, 27]. Contaminants ingested into the air stream can deteriorate the gas path components and lead to three specific damages: mechanical, chemical or thermal [28]. The compressor section is mainly susceptible to mechanical damage by corrosion, erosion, or by fouling. The chemical damage can occur due to condensation or hot corrosion, and the thermal effect arises mainly due to oxidation attack [28]. Each location presents its own set of corrosion, erosion, and fouling conditions. The dust concentration, particle sizes, temperature, and wind direction and speed are factors that control this [28].

To demonstrate the importance of air filtration equipment, the possible effects of airborne containments on the gas turbine should be investigated.

## 6.2 Erosion

Erosion arises in the compressor blades when the compressor is ingested by hard, abrasive particles, such as sand and mineral dusts [16, 23]. As these particles impact upon the compressor blades they cut away a small amount of metal. The erosion rate depends on the kinetic energy of the particles ingested in the compressor, the number of particles impinging per unit time, the angle of impingement, and the mechanical properties of both the particles and the material being eroded [18]. Experience shows that erosion is caused when particle size is above 20 μm. It has also been recognized that erosion is a function of weight and not size when the particle size is larger than 30 μm [29]. The erosion has a great impact on the turbine's life time. Not only does the erosion reduce the aerodynamic performance, but the reduction in cross-sectional area of the compressor blade could lead to serious turbine damage due to increased local stresses (Fig. 6.1) [24].

Figure 6.1 Erosion effect [84]

## 6.3 Corrosion

Usually the average air dust containments do not itself cause corrosion of the compressor blades. However, moisture and aerosols containments such as sea salt may cause corrosion of the compressor (Fig. 6.2) [18]. The most important parameter for initiation of corrosion is the presence of water film on the blades surface [29]. The factors controlling the corrosion rate are the relative humidity and the amount of aerosols containments in the air [29, 23]. The gas turbines that operate near coasts usually experience corrosion more than other gas turbines due to high salt concentrations in the air [18].

Figure 6.2 Corrosion effect [79]

## 6.4 Fouling

Compressor blades fouling typically arise due to one of two elements. The first is solid particulate, mineral and plant matter. The other are the carbon smokes and/or hydrocarbon fumes that create a sticky substance when deposited on the turbine blades [18]. Fouling of the compressor blades is mostly caused by the particles with the greatest surface area, i.e. a size below 2 μm in diameter [18]. The rate at which this fouling takes place is difficult to quantify because it depends not only on the types and quantities of materials ingested, but also on the peculiar properties of the substances that cause them to stick [24,23].

The operation of gas turbines under arctic conditions may seem very different from operation under normal or tropical conditions. Snow and airborne ice crystals are the principle pollutant in the arctic environment [27]. Snow and ice crystals agglomerate quickly in an intake and cause blockage of the intake. The particle size in arctic environment vary from 0,01 µm to 10 µm [18].

## 6.5 Icing formation affect on gas turbines

In environments with low temperatures and high relative humidity, ice formation in the air-intake system represents a multiple problem to the operation. Ice accumulation on the filter elements blocks the filter and leads to a loss of performance due to reduced inlet flow area, increased inlet pressure drop and reduced mass flow which lead to reduced power output and reduced thermal efficiency [38, 40]. Moreover, the filter can ingest unfiltered air which leads to ice accretion on the intake components, bellmouth and IGVs. The ice on the blades can deteriorate air aerodynamic in the passages. So it is possible to experience an axial compressor flow stall and surge [36, 41].

The ice accretion can also cause mechanical damage to the compressor blades as a result of blades vibrations. In extreme cases, ice can shed due to vibratory and/or aerodynamic forces and the resulting impact of these pieces of ice are the hazardous foreign object damage (FOD) (Fig. 6.3) [36, 35]. To protect the gas turbine from icing titanium blading can be introduced as a first step to the front row of compressor blading [35].

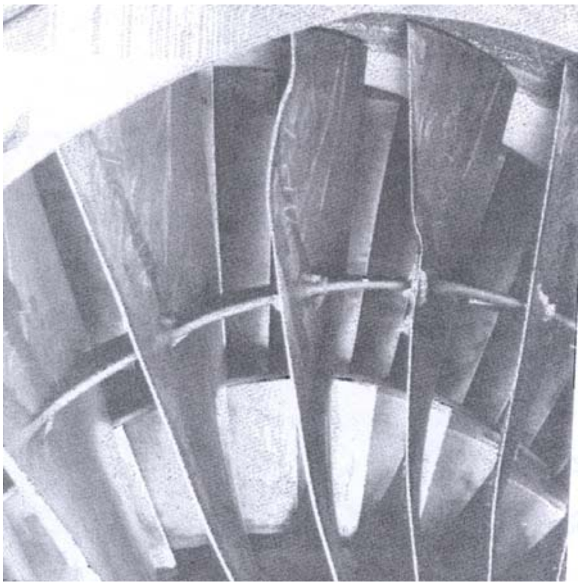

**Figure 6.3 FOD as a result of ice ingestion [36]**

# 7. Gas turbine inlet system

## 7.1 Introduction

Turbine performance and component service life greatly depends on the ability of an air inlet system to reduce or eliminate contaminants entering the system. If these contaminants are not effectively removed, then fouling, erosion, corrosion and compressor blades damage will be the result [19]. Thus air treatment system in order to operate gas turbines economically over the long term can consist of any combination of inlet hoods, filtration system, moisture separation, fogging system and anti-icing system depending on the ambient air quality, dust concentration and the operating environment [23]. These technologies are applied in critical environments during specific circumstances, such as heavy rain and snow, which require a more intense air treatment to operate the gas turbine efficiently. The requirements for gas turbine inlet air filtration have changed dramatically in recent years. Power producers are incessantly looking for ways to maximize the reliability of their gas turbines while concurrently lowering their operating costs. Consequently, the demand on their filtration systems used to protect these units has also steadily increased.

## 7.2 Intake system of the gas turbine

The inlet system of a stationary gas turbine installation has a task to provide an adequate flow of clean air to the compressor [38]. After passing through inlet system components air passes the plenum chamber to the compressor. Inlet system includes inlet hoods, moisture separator and filter system. The (Fig. 7.1) illustrates a generalized configuration for a stationary gas turbine power plant installation and contains all the intake elements found in most generating station applications.

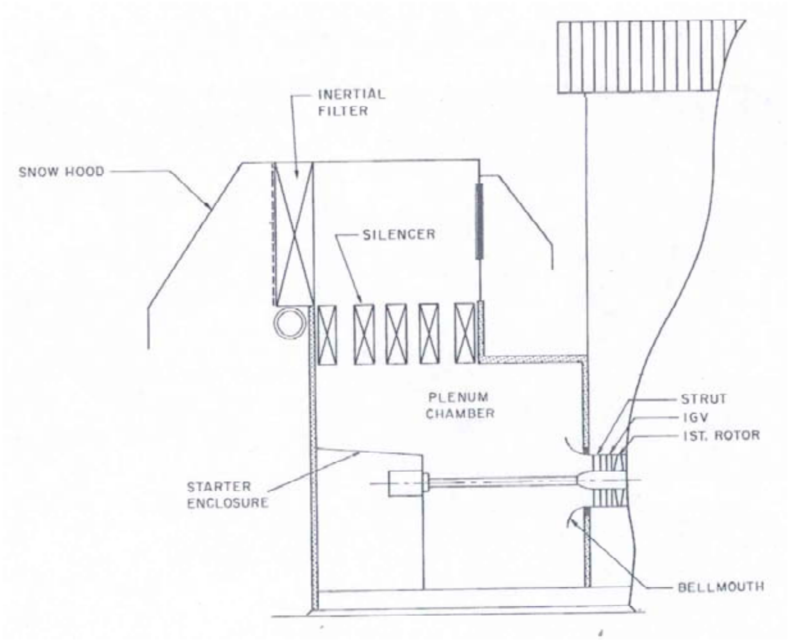

**Figure 7.1 A stationary gas turbine components [36]**

## *7.2.1 Inlet hoods*

Inlet hoods are the first stage in the inlet air treatment system (Fig. 7.2). They have a function to protect the gas turbine from large quantities of snow or freezing rain which can cause icing of inlet components [24]. The concept of operating inlet hoods is based on the inertia separation effect. It depends upon the difference in inertia between heavy particulates and air to achieve separation. The ordinary design of inlet hoods has vertically deflections which cause the inlet air stream to change its direction and flow upwards with low velocity as it enters the system. The large particles with high settling rates cannot follow the intake air stream thus they separate and drain off at the bottom of the inlet hoods. Inlet hoods separation efficiency depends on the velocity of the inlet air stream and particles diameter [36]. Inlet hoods have ability to remove 98% of all particles greater than 15 μm but this efficiency decreases with particle size below 10 μm[21]. They seldom require cleaning. Their disadvantage is the low efficiency in removing small particles such as mist [21].

**Figure 7.2 Inlet hoods [36, 65]**

### 7.2.2 Moisture separators

This device comes as the second stage in the inlet air treatment system in the gas turbine. They have a function to remove moisture and small liquid droplets from the air stream [21, 29]. This is very important because if the moisture or small water droplets reach the compressor inlet they can cause severe damage such as corrosion or ice formation on the blades of the compressor and the turbine bleeds. Moisture separators have a simple design. They are consisting of a single or three stage system. Single stage system consists of a series of vertically hooked vanes that makes the incoming air experience several direction changes (Fig. 7.3) [24]. Thus water droplets gathered upon the sides of the vanes, being unable to follow the air due to their greater mass and they fall by gravity to a collection sump. A single stage cannot remove more than 95% of droplets smaller than 5 μm [21].

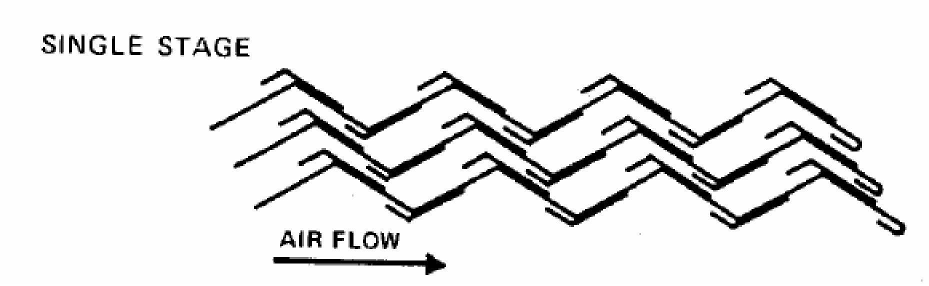

**Figure 7.3 Single stage moisture separator [29]**

To remove droplets that are smaller than 5 μm in size, more stages are needed. Therfore a three- stage system is applied to achieve this. It consists of a first stage vane followed by a *coalescer pad* and then a second vane (Fig. 7.4) [24]. The coalescer pad purpose is to catch the smaller droplets into 1 μm [29]. There is a possible at the captured droplets by coalescer drain down through the pad and agglomerate with other droplets to form larger droplets. Therefore the third stage which is similar to the first stage stops them. A tree stage vane-coalescer-vane can achieve an efficiency of water removal from the air stream of 99.9 % above 10 μm; 99.5% above 5 μm and 87% down to 1 μm [21].

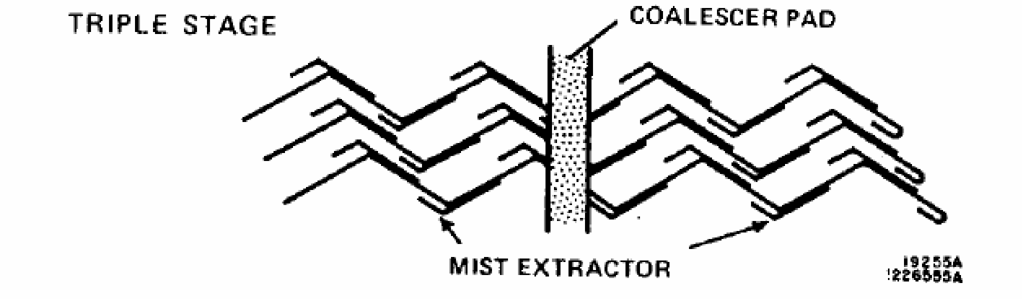

**Figure 7.4 Triple stage moisture seperator [29]**

### *7.2.3 Filter system*

Filter system for gas turbine is an essential part in the inlet air treatment system. The previously described protection components, remove a part of the air containments specially those with large size. But the air carries a mixture of particles in a very wide distribution range. That means that the air still is carrying a great part of small containments which may constitute hazard on the gas turbine. The installation of filtration system prevents the gas turbine from physical damage, increases reliability, and reduces turbine maintenance and lower service cost [26].
Filters which are used in gas turbine applications can be classified according to their ability to separate containments to pre filters, fine filters or high efficiency filters [29]. Unfortunately, there are not any specific classifications methods for gas turbine filters. Therefore general ventilation standard filtration has to be used [14]. Filter elements normally use pleated media in order to increase the available surface area, and increase dust-holding capacity [24]. They take usually a cylindrical shape (Fig. 7.5)

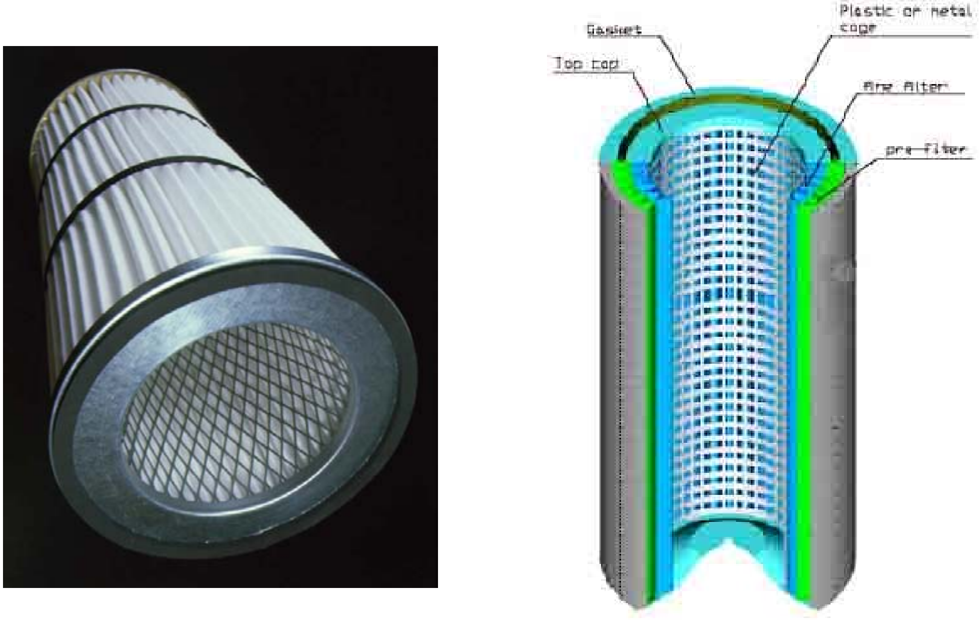

**Figure 7.5 Filter elements [80]**

There are two types of filters that service in the gas turbine applications, static filter and pulse-jet self cleaning filter system. There are two differences between them. The first one is that the pulse filter clean it self frequently by pressurized air [17, 22]. The other different is the way filter media filters the incoming air.

## 7.3 Static filters

Static filter system or as is called multistage conventional system consists of two or more air-filter stages. The system which is still currently applied today consists of three stages [19]. A first stage contains weather protective section, pre- filter as a second stage and fine filter as third stage (Fig. 7.6).

*The first stage* is a weather protective stage which would include one or more of the following components [19]:

- Inlet hoods
- Bird screens
- Moisture separators

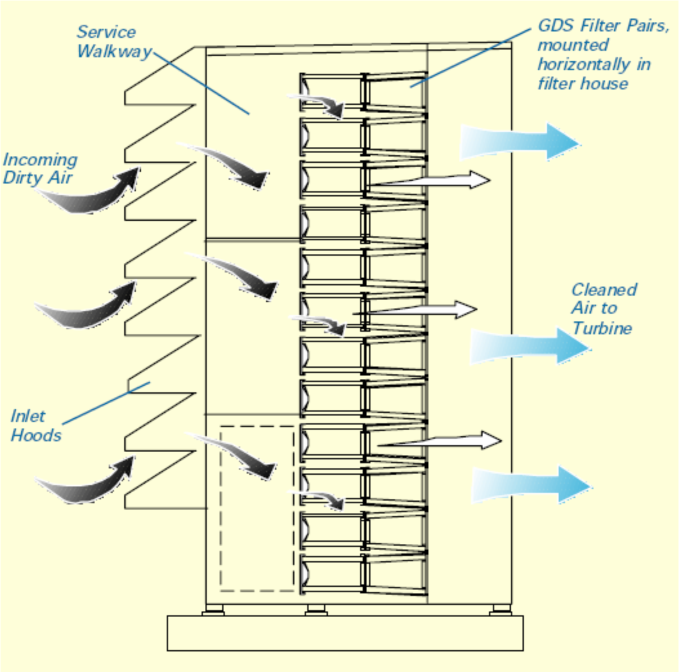

**Figure 7.6 Static filter [67]**

*The second stage* in the static filter is always the pre- filter which has a medium efficiency. The pre-filter covers the expensive high efficiency filter and extends its life [24]. Pre-filter is used to protect the gas turbine from a major part of particulates like coarse dust or the airborne such as seeds, ash, and insects. But pre-filter has limited effect against small particles. It is made of glass fiber or synthetic fibers [29]. It collects particles with help of inertia effect. This happened when big particles as effect of its inertia cannot follow the air flow and collide within the depth of the filter media (Fig. 7.7) [15, 21]. This effect depends upon air flow velocity and particles size [29]. The particles captured by pre-filter are typically above 1 µm [15]. The pre-filter is economical, so is typically changed more often.

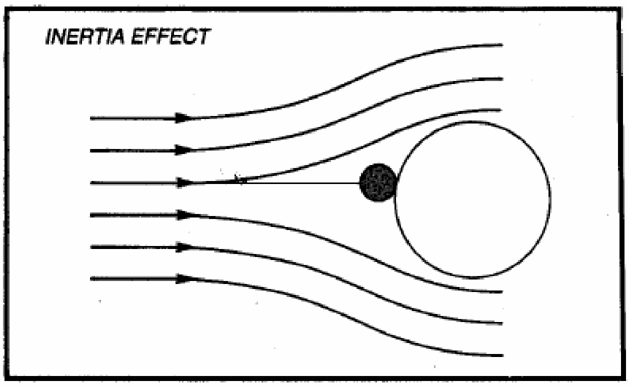

**Figure 7.7 Inertia effects of big particles [29]**

*The third stage* is the most important stage in the static filter and it's existing always in the filter system as a final stage. Fine filter provides a maximum protection against very small dirt/dust particles including those as smaller than 1 µm [29]. This technology consists of special medium fine diameter fibers. Because the collection efficiency of fine filter is very high, the air quality in front of the gas turbine is also high. Particles collection in fine filter is due to *interception* and *diffusion* effects [15, 21]. The interception effects occur when small light particles collide within the media of the filter and are retained to the fibers by the forces of intermolecular attraction [15]. Particles captured by interception are typically above 1 µm [15]. The interception effect increases with increasing particle size and decreasing fiber diameter [29]. A filter medium with a good interception effect contains a large number of fibers. While particles with a diameter less than 1 µm will capture by the influenced of the *Brownain motion* causing small particles to contact or move close to a fiber[29]. This effect on the particles motion is called diffusion effect (Fig. 7.8). Particles are retained to the fiber by diffusion vary from the smallest particles that can exist up to around 0.3-1 µm [15]. The efficiency of capture by diffusion increases as particle size and velocity decrease [29].

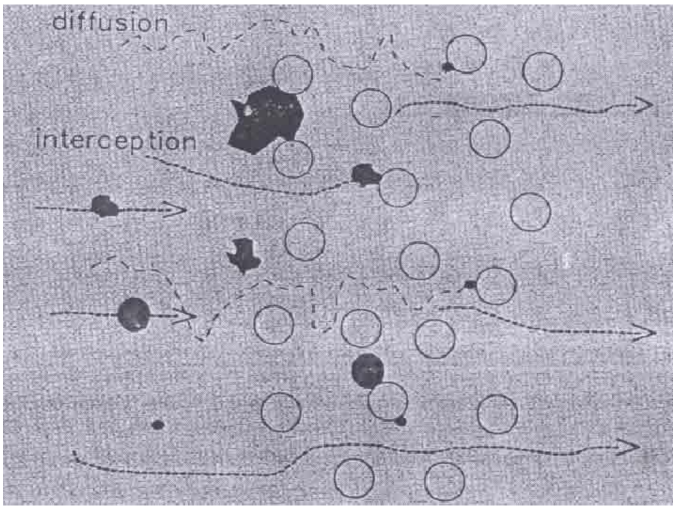

**Figure 7.8 Diffusion and interception effect [21]**

# 7.4 Pulse-jet self cleaning air filters

## *7.4.1 Introduction*

The pulse-jet self cleaning air filtration systems have been applied in many gas turbine applications since it has introduced in 1976[17]. Pulse clean filter systems were designed in the beginning for using on gas turbines which operates in desert environments to overcome problems of static filter blockage during dust storm activity in the Middle East, Saudi Arabian by ARAMCO Company [22]. This filter has been widely accepted all over the world as a good solution for protection gas turbine under desert environments and remote locations that need long filter service life. Pulse filters have been examined in arctic environments where hazards of blowing snow, hoarfrost, and ice fog are problem to the gas turbine. The first pulse-jet self cleaning air filtration system applied to a cold weather application was ( Solar Turbines, Inc. Saturn gas compressor set, Union Oil application, Kenai, Alaska, 1976) [17].

## *7.4.2 Concept*

Pulse filters are filters that, with pressurized air, remove the particles located at the filter surface. They are called pulse filters because of the intense short time air flow through the filters. Self cleaning filter combines the effectiveness of the high-efficiency filter with low maintenance [24]. These filters media have ability to renew themselves automatically when they become loaded with dust. There are two types of pulse-jet self cleaning air filters, convectional types "vertical pulse filters" and new concept "horizontal pulse filters" [25]. The difference between them comes from two modifications; the filter arrangement and the incoming air flow direction.

### 7.4.2.1 Convectional pulse-jet self- cleaning air filter

The concept of the convectional pulse-jet self- cleaning air filter is simple. The pulse- jet self cleaning air filters consist of high- efficiency filter elements in the form of cylindrical cartridges which are attached vertically (Fig. 7.9).

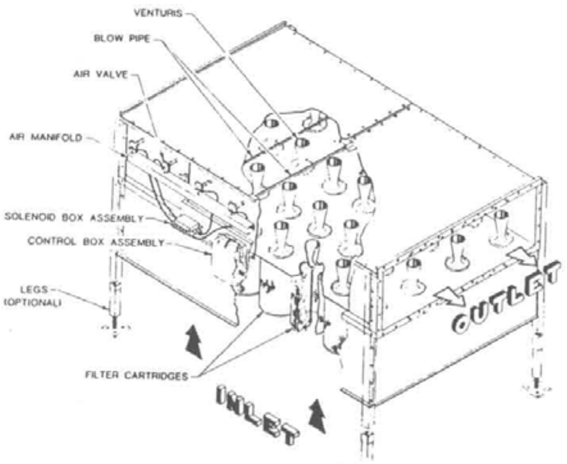

**Figure 7.9 convectional pulse-jet self- cleaning air filter [22]**

Above each filter, in the clean air plenum is a venture flow nozzle. During normal operation ambient air flows upward through the venture and finally to the turbine. During this the filter is operating as just a high-efficiency filter. But when the ice and snow accumulate on the surface of the elements, the pressure drop across the cartridges will continually increase until it reaches a specific limit when the automatic pulse cleaning is activated (Fig. 7.10) [66]. A pressure switch senses that the pressure drop has reached its upper limit. This gives a signal to open the valve and allows a brief back-pulse of air compressed to go out through the blow pipe. The compressed air comes either from the gas turbine compressor, or is derived from an auxiliary source [22].

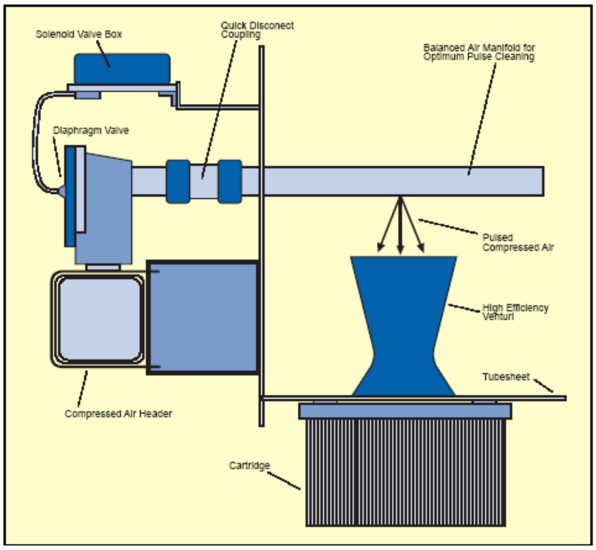

Figure 7.10 Pulse filter [66]

The compressed air waves blow away the accumulated snow and ice on the filters elements (Fig. 7.11). A row of cartridges is pulsed at one time then another row after that and the pulse-cleaning procedure is repeated [24].

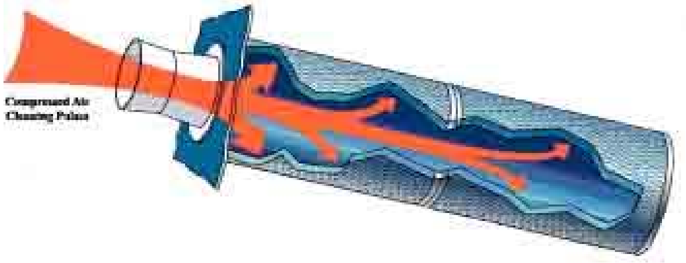

Figure 7.11 Pulsed element [84]

The operation will continues till the overall pressure drop reaches a present lower limit. A single cleaning cycle is usually completed in 20 to 30 minutes [24].

### 7.4.2.2 New concept

This new concept has been introduced for the first time on gas turbines in 1985[25]. This new system has the same principle as the conventional self cleaning pulse air filters has in cleaning the filter media from dusts. The different is that the filter elements are installed horizontally against a vertical wall separating the clean air from the dirty air side (Fig. 7.12).There are protected against the atmospheric conditions by an outside capsulating shell, which generates the downward direction of the air stream through the filter elements. The ambient air flow comes first through the inlet hoods to the filter. The dusts which are transported with ambient air flow are captured by the high efficiency media and a dust cake forms on the filter surface. As the dusts build up on the elements, the pressure drop increases slowly. This gives a signal to release a compressed air to clean the filter media. The elements are cleaned sequentially, top to bottom. The advantages with this new concept are improving turbine protection and have a compact size because they require less foot space [25]. The new pulse-jet cleaning filter systems are the most employed now in gas turbine applications because these advantages over the conventional pulse filter systems.

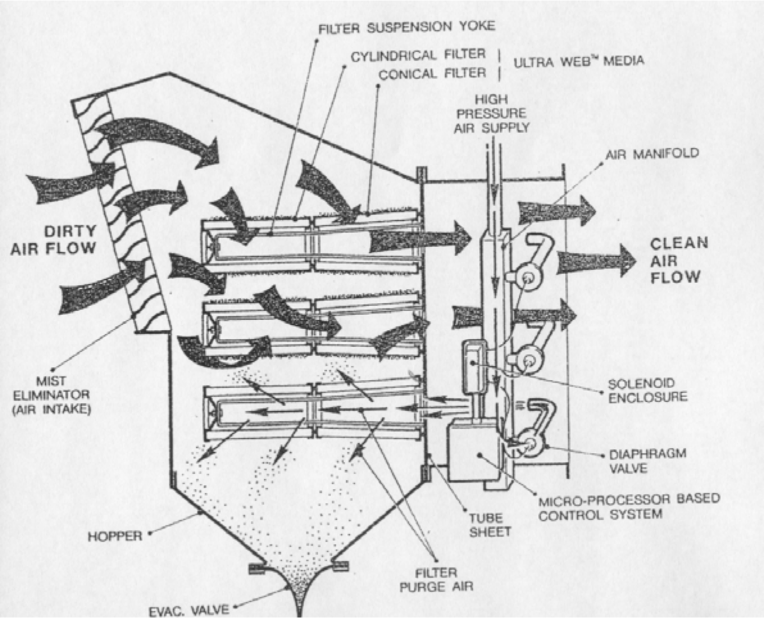

**Figure 7.12 new concept pulse-jet self cleaning filter [25]**

The media surface of the pulse-jet self cleaning filter collects particles with straining effect [21]. Straining effect means that particles are captured on the surface of the media. To achieve that the particles have to have a diameter greater than the clearance between two fibers thus these particles can not pass and will be retained in the filter medium (Fig. 7.13). As a consequence this effect is limited to particles around 10 µm or larger. The smaller particles, especially 2 µm and smaller are not arrested at all by this filter [21].

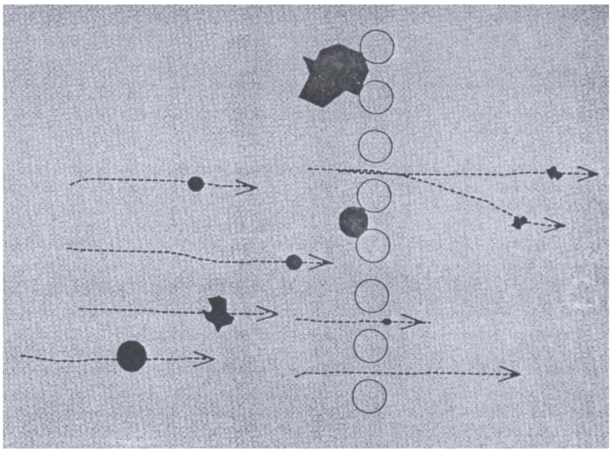

**Figure 7.13 straining effect [21]**

From this it is apparent that pulse filter has a high captured efficiency with coarse dense materials. And cleaning a pulse-jet filter from them is a simple matter since the heavy dust particles are easy to shake loose from filter media and they are able to move against the incoming air and not are drawn back onto the filter. In contrary the pulse filter has low efficiency against small particles [15, 23]. Moreover the pulse clean filter cannot get rid of small particles from the media and even if it could, it not would be able to maintain a sufficiently large reserve air flow to remove the particles from the influence of the incoming air [15, 20]. That's mean they will be immediately drawn back into the filter as soon as the pulse flow stops. The pulse-jet filter has a low efficiency until the dusts quickly agglomerate on the filter media after. This leads to close the pores between the filter fibers and increases the filter efficiency against small particles with time. This problem was overcomed by seeding or throwing dust onto the filter media when the gas turbine is started [15]. In other words the pulse filter is particularly effective against dry high concentrated coarse dust. The other disadvantage with pulse filter is that with high percentage of sticky and gooey, unburned hydrocarbons and under environment with high moisture content in the air it will be so difficult to clean the filter to the acceptable level Δp [15].

The filter elements are replaced when they begins to show signs of deterioration caused by heat and ultraviolet rays from the sun, or when the cleaning cycle no longer are able to restore pressure drop to the acceptable limit [24,65].

## 7.5 Filter selection

Intake air filtration for gas turbine engines is an essential part of the installation. Care must be taken during design to select a filter appropriate to the environment to increased reliability of the gas turbine and reduce engine maintenance. It's clear that there is no single filtration system that will suit all applications. Each has to be designed according to the engines requirement and the nature of the ambient air. This selection depends on containments sorts, particles size, relative humidity and precipitation [20,21]. If the gas turbine operates in warm climate which means high temperature and high humidity conditions, the gas turbine might be equipped with cooling system to decrease the ambient air temperature which leads to increasing air density and mass flow rate. As a result the gas turbine output power will increase. While with arctic gas turbine application inlet system of the gas turbine must be equipped with anti-icing system. Ice can block inlet filtration equipment, increase pressure drop across inlet components which leading to performance loss [27]. However the information on air containments for selecting an air filter on a new installation is usually lacking. Seldom are air quality tests undertaken during the project planning stage. Air filter selections tend to be unscientific often based on individual experience and prejudice [21]. As an example ARAMCO has tested pulse-jet self cleaning filters in sandstorm conditions in the Middle East deserts, Saudi Arabia. This system did well and overcame problems of static filter blockage during dust storm activity [22]. Experience in using the pulse filter in arctic environments has shown that pulse filters prevent the gas turbine inlet system from ice building without any scientific explanation for this.

The efficiency of static filter and pulse filter is still under debate. The static filter's advantage is its high efficiency against big and small particles from the start operation in the gas turbine. It's less efficient in dust storms and gives a bad protection from high concentrations of coarse dust [15]. In contrary, pulse filter has advantage over static filter that it can pulse away particles that accumulate on its filter media. But it has low efficiency against small particles and moisture environments [15]. Therefore in many installations pulse clean filter is used as a pre-filter and static filter is used as a second stage of filtration to ensure a high level of filtration efficiency.

# 8. Anti-icing and De-icing systems

The primary aim for an icing protection system is to prevent or limit ice accretion within the gas turbine intake system. The complexities of inlet system for stationary gas turbine applications often limit the possibility of guaranteeing free icing inlet system [36]. Two terms occurs frequently in the discussions of icing protection systems; “Anti-icing” and “De-icing” and it’s important to distinguish between them. Anti-icing protection system includes all icing protection schemes that prevent the formation or ice accretion on the inlet system components. De-icing systems on the other hand, includes all icing protection systems that permit a certain ice accretion to form and then promotes its removal before it can reach hazardous proportions [36]. The icing protection systems can also be divided with respect to their icing protection technique into the following systems: thermal system, chemical system, inertial system and mechanical system [36].

## 8.1 Thermal systems

This system uses heat source to avoid ice formation in the turbine inlet system. The heat can be used to warm up ambient cooled inlet temperature or to warm up the icing surfaces so the ice can’t form on it. The thermal systems prevent the gas turbine both from condensate icing and precipitate icing [36]. There are two well-known systems which use heat source to protect the inlet system of the gas turbine from icing: inlet heating system and components heating.

### *8.1.1 Inlet heating system*

Inlet heating system is a type of anti-icing system. Inlet heating systems operate by transferring heat from hot gas from some source to the cold ambient air at the entrance of the inlet system. The hot gas is often air but hot exhaust gases can also be used [24]. The advantage of charge heating is that, if the temperature is raised sufficiently, icing cannot take place in the gas turbine intake system.

#### 8.1.1.1 Compressor inlet bleeds heating system

This is a popular choice for simple cycle installations and peaking units (Fig. 8.1). A compressor bleed anti-icing system accomplishes this by using a portion of the compressor discharge air for this purpose. This air has typically temperature around 350 [$C^o$] depending on the ambient conditions and turbine model [24]. The greatest advantage with this system is that the heat source can increase the inlet air temperature without affecting the water content in the inlet air, that is, without affecting the absolute humidity of the inlet air. This is because the hot air that extracts from the compressor is dry and warm enough. The system is basically quite simple, since only one control valve is required. It is a well proven technology and usually quite reliable and controllable [38].

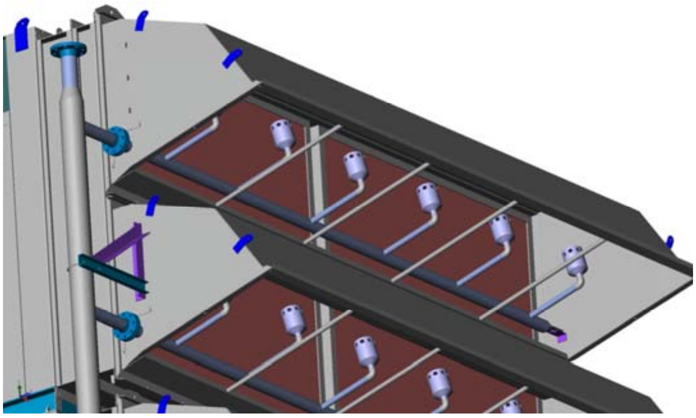

**Figure 8.1 Compressor inlet bleeds heating system [85]**

Relative to the other systems, it is generally the least expensive. In addition to this, the relatively high pressure at which heating air is discharged promotes uniform mixing. Due to the absence of large dampers, it is quick-acting [24]. The biggest disadvantage with bleed-air system is the performance loss which depends upon ambient conditions. This performance loss can range from 2% to 5% of the total power output [38]. For some applications bleed air noise can be a problem. It can be omitted by added silencers to reduce the sound level [38]. Compressor inlet bleeds heating systems have seen service for many years and have given excellent results. System schema illustrates on (Fig. 8.2).

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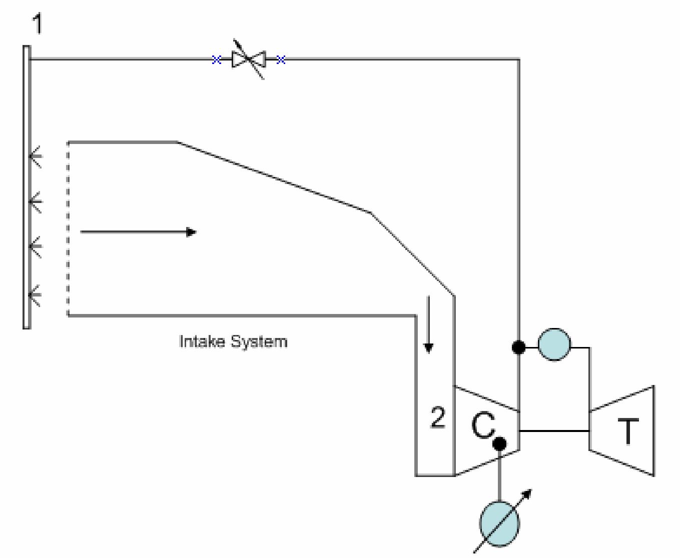

**Figure 8.2 Compressor inlet bleeds heating system [34]**

### 8.1.1.2 Exhaust recirculation system

This system operates by mixing a potion of the hot exhaust gas with the cold ambient inlet air (Fig. 8.3). It is clear that the moisture present in exhaust gas creates problems when exhaust gas is the source of heat [24]. Exhaust anti-icing system is not so effective because of it has great disadvantages. The biggest disadvantage in this system is the exhaust gases which include many impurities and are products of the combustion process. The direct injection of exhaust gases can lead to compressor fouling [24]. The amount of fouling depends on the fuel used and combustion characteristics of the turbine. Gaseous fuels result in fewer fouling problems than liquid fuels [24]. Moreover there are difficulties in directing exhaust gas in the exhaust gas duct to the inlet system because of exhaust gases have very low pressure. This limitation can be solved by install fans or blowers but the equipment must be designed to withstand the high exhaust temperature. Exhaust recirculation anti-icing system is generally difficult to achieve because of the concept requires extreme care to meet the special requirements of compressor temperature uniformly [24]. While this system has advantage over compressor inlet bleeds heating anti-icing system. It has less influence on the turbine performance.

In generally this system has been found to be more successful in relatively moderate environments than extremely cold climates. With relatively moderate environment, the relative humidity is lower. In other word the maximum capacity of air to hold moisture are greater. When hot exhaust gases which includes moisture mixes with cold ambient air the relative humidity increases but it didn't reach the maximum capacity. Thus there is room for more moisture in the air. In contrast with extremely cold environments the relative humidity is high. That's mean when the hot exhaust gases mixes with cold air the water content in the air will increase and it will be close to the maximum water content. Thus it will be easier to reach the saturation point and condensation will be the result [24].

This system is more effective with a compressor that runs at constant load and high exhaust gas temperature, than with a compressor that runs at part load with less exhaust gas temperature. When compressor runs with part load the parameters will be changes dynamically. As the result the design points will change continuality [24].

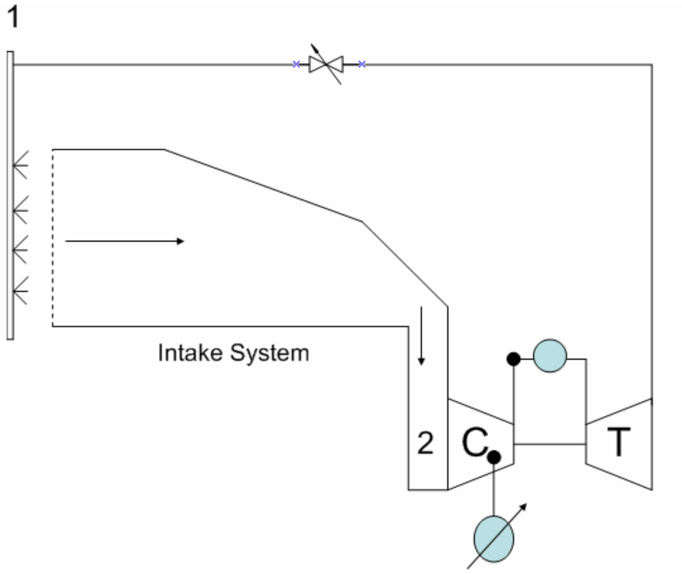

**Figure 8.3 Exhaust recirculation anti-icing system**

### 8.1.1.3 Heat recovery system

The heat recovery anti-icing system was designed to have the advantages associated with a "dry" heating system and having less effect on performance than compressor bleed system. The system works by passing exhaust gases from the turbine outlet through a heat exchanger located in the exhaust duct. The ambient air flow draws from a specific point after the filter system and with help of fan the air blows through the heat exchanger [24]. The exhaust gases warm up the ambient air temperature by convection heat. The exhaust gases then sent to atmosphere through a secondary exhaust duct while the warm ambient air will be sent to the inlet of the filter system to warm up the incoming air to the gas turbine (Fig. 8.4). To force enough hot gas into the heat exchanger, it is necessary to install an adjustable damper in the main exhaust stack. This damper is never closed completely but can be adjusted to force additional hot-gas flow to the heat exchanger when higher inlet temperature rises is required [24]. The centrifugal blower does not get iced because it located after the filter system so it handles only warmed air. The heat recovery system has relatively little effect on performance and this is the advantage with this system. However heat recovery anti-icing is more complex and more expensive then compressor bleed system. In addition this system has a great volume which takes a place from the site [38].

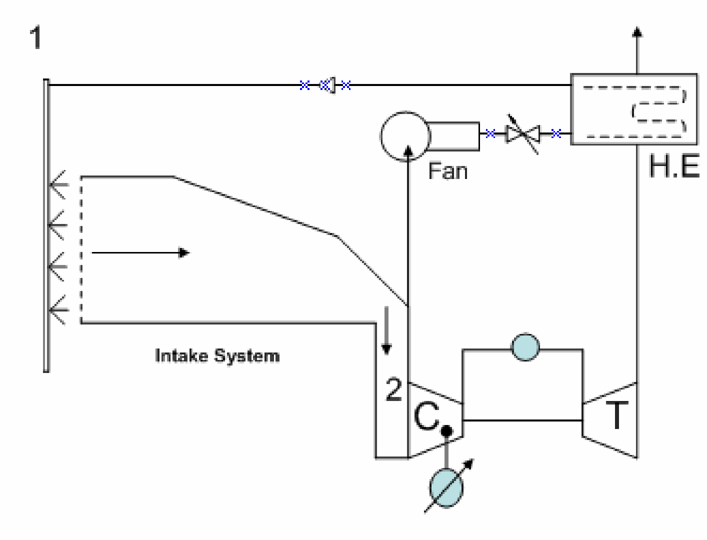

**Figure 8.4 Heat recovery anti-icing system**

### 8.1.1.4 Hot water heat exchanger

Preceding systems are aimed to protecting simple cycle gas turbines from ice forms on the inlet system components. But in case of operating power station gas turbine in "combined cycle" there is no reason to extract air from the compressor that affects the turbine performance. It's more practical to use a free heat source which is warm water from the process of producing steam. The system is a simple water/air heat exchanger. The warm water enters the heat exchanger with temperature around 80 $C^o$ and the ambient cold air enters the heat exchanger with reverse direction. The heat transfers from warm water to ambient air by convictive. The heat exchanger sites in the inlet system of the stationary gas turbine previous to the filter system. The temperature rising of the ambient air is controlled by regulate the mass flow of the warm water in the heat exchanger [39]. Usually the warm water blends with freezing point depression to avoid freezing of water in the heat exchanger when anti-icing system is shut off. Water/glycol mixture is the most usable in this system (Fig. 8.5).

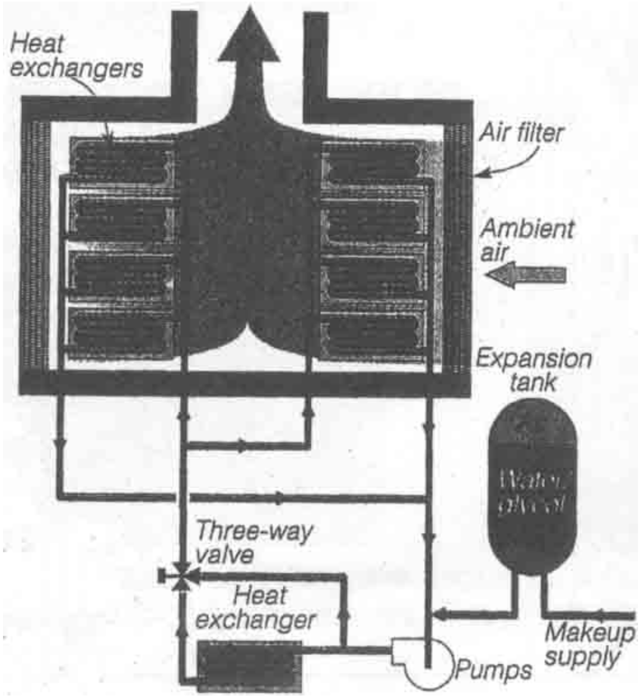

**Figure 8.5 Hot water heat exchanger system [39]**

## *8.1.2 Component Heating*

Heat is applied to an area to eliminate or prevent the formation of ice. The heat evaporates or prevents supercooled water droplets from freezing. Most aero-derived engines come equipped with component heating but this system is unlikely in ground installations. Two heat sources are used in this system to warm up the icing surface; electricity and compressor bleed air [36].

### 8.1.2.1 Electrothermal system

Electrothermal system this system consists of resistance wires are imbedded in rubber pads which are mounted on the icing surface which has to be protected [36]. This system’s advantage is that it only heats the icing points [41]. However, it requires the exact critical points where ice can form. Since the ice forming process is very complex, it’s difficult to determine these critical points. Therefore more than one electrical heater can be used to cover up all these points. BFGoodrich has developed an electrothemal system for the rotor blades of the Army Apache AH-64 helicopter (Fig. 8.6). Electrothemal system consists of a source of electrically generated heat and a control system. The system pulverizes ice into small particles and removes layers of ice as thin as frost or as thick as an inch of glaze ice [69].

**Figure 8.6 Electrothermal system [69]**

Hongchang Electric Heater Products Factory, which has established in 1996, introduced heating components which are made of metal electrothermal film. I think both of these systems can be used in the ground gas turbine applications (Fig. 8.7) [70].

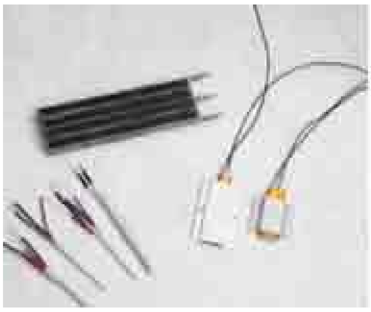

**Figure 8.7 Electrothermal system [70]**

### 8.1.2.2 Compressor bleeds air

Compressor bleeds air is similar to blades cooling technique. This can be achieved by drilling canals in the components which have a great hazard for ice accretion such as IGVs and struts. The hot air passes through this canals and warm up the surfaces of these components. Hot air can be extracts from the compressor or exhaust gases from combustion products. This system is very expensive because of it is a very complicated and precise manufacturing process [36].

Compressor heating system is rarely used in stationary gas turbine installations. It is more common in aero applications. Aircraft wing and propeller roots are common locations for electrical pads [36].

## 8.2 Chemical system

A chemical system counts as an anti-icing system. This system operates by mixing liquid water with freezing point depressant, e.g. ethylene, glycol and isopropyl- alcohol [68]. This achieves when two chemical substances are mixed together, the freezing point of the resultant mixture will be lower than the freezing point of either constituent [53]. The first substance is the solvent which is a liquid that dissolves a solid, liquid or gaseous solute, resulting in a solution. The most common solvent in gas turbine applications is water [77]. Freezing point depression is the difference between the freezing points of a pure solvent and a solution mixed with a solute [75, 76]. Fluid ice protection systems operate on the principle that the surface to be protected is coated with a fluid that acts as a freezing point depressant [53]. Current systems normally use a glycol- based fluid [39]. When super cooled water droplets hit the surface, they combine with the fluid to form a mixture with a freezing temperature below the ambient air temperature. Fluid is distributed onto the surface by pumping it under pressure. The way to accomplishing this is spray nozzles (Fig. 8.8) [53].

**Figure 8.8 Spray nozzle [53]**

With using one of these anti-icing solutes considerations have been taken to the following aspects:

- **Alcohols** (methanol, ethanol, isopropanol). Main problems with these solutes are safety. They have low flash point and high volatility. Therefore there is a hazard for explosion.
- **Ethylene glycol**. The problem with this solute is it forms sticky deposits on compressor blades.
- **Propylene glycol**. Generally recognized as the most suitable anti-icing solute for gas turbine applications. It has a high flash point, is not toxic and does not form sticky deposits during the process [68].

Water/glycol mixture is the most usable in the stationary gas turbine. The ratio for most [water/glycol] systems is 50%: 50% [39].

The following figure (Fig. 8.9) was found in a published report [36], but has not been checked out in detail. From this figure it can be noticed that with mixing water with 20% of ethylene glycol the freezing point depresses from 0 [$C^o$] to -6 [$C^o$] [36].

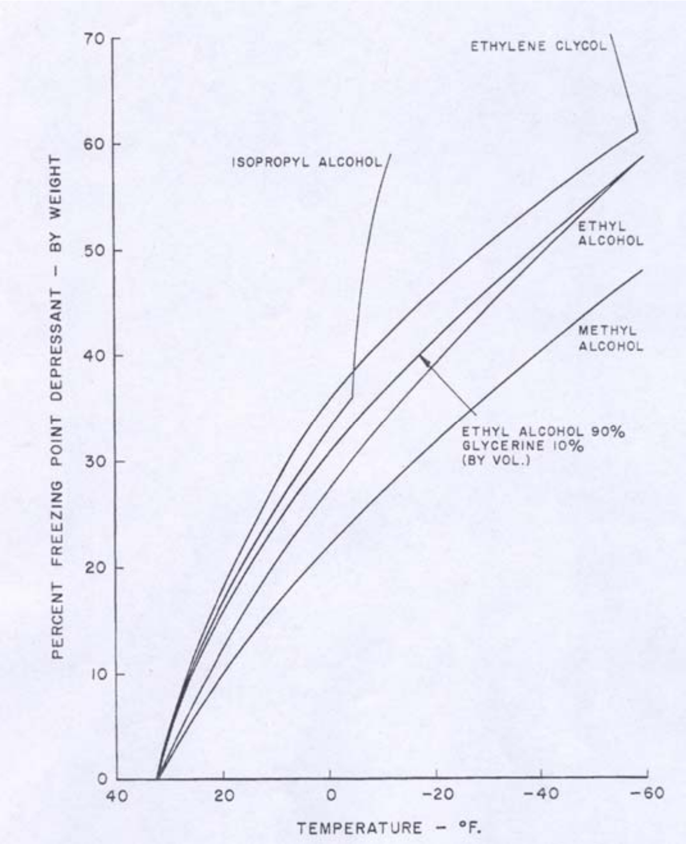

**Figure 8.9 Freezing point depresses [36]**

The chemical anti-icing method is rarely used. This is because of the gas turbine protection period has to be extend over a long period under icing environment which is costly [36]. Chemical system is usually used with cleaning of the compressor under low temperature conditions.

## 8.3 Mechanical system

The mechanical system is a de-icing system. Mechanical de-icing at stationary installations takes the form of manual brushing of hoarfrost from the filter. Electrical brushing systems can be used also [36].

## 8.4 Inertial system

The inertial system operates by separation of particles from an air-stream that carries them. It achieves this by forcing the air stream to change its direction drastically. Inertial separators are widely used in stationary installations for dust and sand protection. They handle also hail and freezing rain problem. In cases the hoarfrost forms inside the inertial separators can usually be removed by brushing. The best separator is the inlet hood [36].

## 8.5 Other systems

In this section two systems will be presented that can be used as an anti-icing system. The first system is AIMS system which is a concept system from Donaldson Company. The second system is water heat exchanger which is usually used in combined cycle power plant as the most suitable anti-icing system [36].

### 8.5.1 AIMS system

1n 1973, Donaldson Company, started a program to study the causes of stationary turbine inlet icing and to develop a system to prevent it. The new system is AIMS system which is a heat exchanger/ moisture separator. The new system works as a heat exchanger with using exhaust gases from the combustion as heat source, and as a moisture separator. The concept of AIMS system is simple (Fig. 8.10) [33].

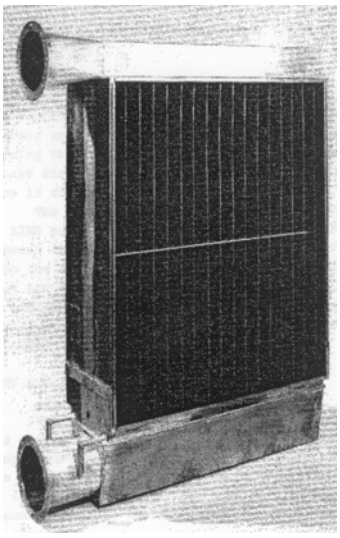

**Figure 8.10 AIMS system [33]**

It is series of hollow vanes arranged so that the intake air stream must make sharp turns as it passes through the AIMS system. These turns generate inertial forces on the water droplets entrained in the air flow and cause them to impact on the vanes. Gravity then pulls the droplets to the bottom of the AIMS where they are drained off. Exhaust gas is drawn through the inside of the vanes thereby preventing them from becoming iced and warming the intake air by convective heat transfer (Fig. 8.11). Thus intake air temperature rises versus exhaust gas flow temperature decrease [33].

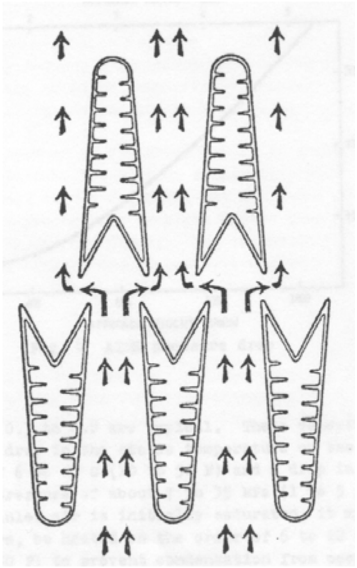

**Figure 8.11 AIMS system [33]**

The heating requirement is, of course, lessened if some of this water can be separated from the air. Weather hoods can prevent most rain drops from entering an inlet system but they are ineffective on fog droplets and this is the purpose of designing the AIMS system to work as moisture separator. AIMS advantages are using free source of heat exhaust gas and this system cannot cause fouling of compressor blade since it does not blend exhaust gas with intake air. Furthermore AIMS system can prevent both precipitate and condensate icing by preventing the inlet air temperature from dropping below 0 C$^{o}$.
The system was installed at Wamsutter, Wyoming, USA in 1974 on the inlet of Solar CENTAUR, turbine owned by Colorade Interstate Gas Company.During the 1974/1975 winter; five icing incidents occurred at the Wamsutter sit and it was just frost [33].

### 8.5.2 Pulse-jet self cleaning filters

The concept of pulse-jet self cleaning filters has been explained in the gas turbine inlet system section 7. After several years of using pulse filter in arctic environment experience shows that pulse filter can remove hoarfrost in much the same way that they clean themselves of dust [15]. In discussion of using the pulse filter as an anti-icing system instead of other conventional anti-icing systems come up two important questions. The first question is if there will be ice formation in the gas turbine inlet system due to temperature depression with using the self cleaning filters or not. A test has been done on a LM 2500 gas turbine in western Canada during the 1981-82 winters. This gas turbine which has a self- cleaning inlet air filter with no inlet heating had completed a full year operation without any problems. During the test period frost was visible on the inlet guide vanes for one period of less than a minute, but there were no ice build up, and no icing problems [24]. Many gas turbine manufacturers now use self-cleaning filters as an anti-icing system and the gas turbines operate without any problem. According to Siemens rapport, Siemens has several gas turbines equipped with pulse self cleaning filter. For SGT-600 there are 29 gas turbines distributed in Sweden, Denmark, Germany, England, Holland and Palestine. While for SGT-800 there are six gas turbines that operate with pulse filters in USA, England and France. So it's perceptible that pulse filters can be used efficiently as anti-icing systems. The second question is why just the pulse clean filter can operate as an anti-icing system and the static filter cannot. General Electric explains this with two explanations. The first explanation is when the ambient conditions are favorable for icing; the frost will form on outside of the filters elements. Moisture which freezes on the filters is no longer available to cause problems at the bellmouth. The second explanation is the temperature in the inlet bellmouth is about 2 to 3 $C^o$ warmer than the air leaving the filter components [24]. However these two explanations have weakness. They are valid both in static filter and pulse filter moreover they don't explain condensate icing. In other word they give explanation just for water droplets that have been held by the filter. But the problem with icing in the gas turbine is the water vapor which condenses from the air as a result of air acceleration in the inlet system. Pulse filter manufacturer Donaldson explains this with that they pulse their filters media frequently every day. Thus it is probable that air pulses also part of moisture from the air. This explanation does not explain condensate icing. I didn't find any convincing explanation of the behavior of pulse filter. I didn't either find any information showing that a gas turbine has been exposed to ice ingestion as a result of using static filter as an anti-icing system. Clearly there is a lack of experiences around this subject. I have theory that possibly will explain why pulse filter can work as anti-icing system.

#### 8.5.2.1 My theory around why pulse filter can work as anti-icing system

My theory around pulse filters is based on ice physics. The process of freezing water vapor in the air to ice is called *Nucleation* .Before explaining my theory I have to introduce the background of my theory which is the nucleation process.

Nucleation process: Ice is the result of a liquid (water) becoming a solid (ice) by an event called nucleation. In order to freeze, a water droplet must first reach its nucleation temperature. There are two types of nucleation, homogeneous and heterogeneous nucleation.

Homogeneous nucleation occurs in pure water in which there is no contact with any other foreign substance or surface. With homogeneous nucleation, the conversion of the liquid state to solid state is done by lowering temperatures. The nucleation process (freezing) for pure water will take place at temperature as low as -40 [$C^o$]. In homogeneous nucleation, the nucleation begins when a very small volume of water molecules reaches the solid state. This small volume of molecules is called the embryo and becomes the basis for further growth until all of the water is converted to ice (Fig. 8.12). The growth process is controlled by the rate of removal of the latent heat being released [62, 10].

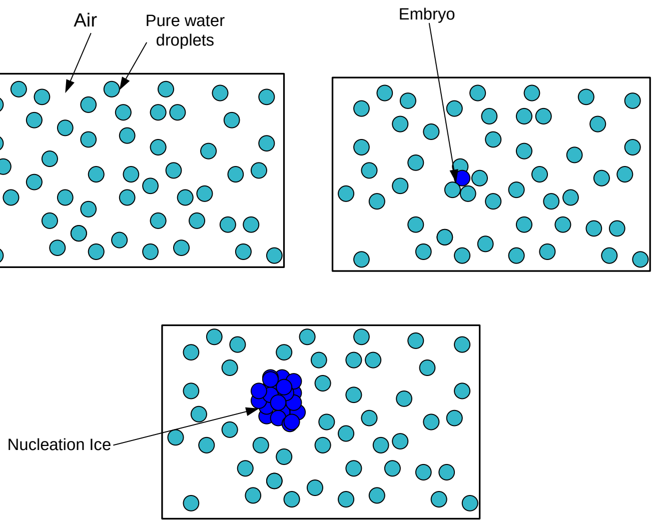

**Figure 8.12 Homogeneous nucleation**

Hetergeneous nucleation occurs when ice forms at temperatures above -40 [C$^o$] due to the presence of a foreign material in the water. This foreign material acts as the embryo and grows more rapidly than embryos of pure water. The location at which an ice embryo is formed is called an ice-nucleating site (Fig. 8.13). There are many materials and substances which act as nucleators; each one promotes freezing at a specific temperature or nucleation temperature. These nucleators can be dust, silt or other particles in the air [62, 10].

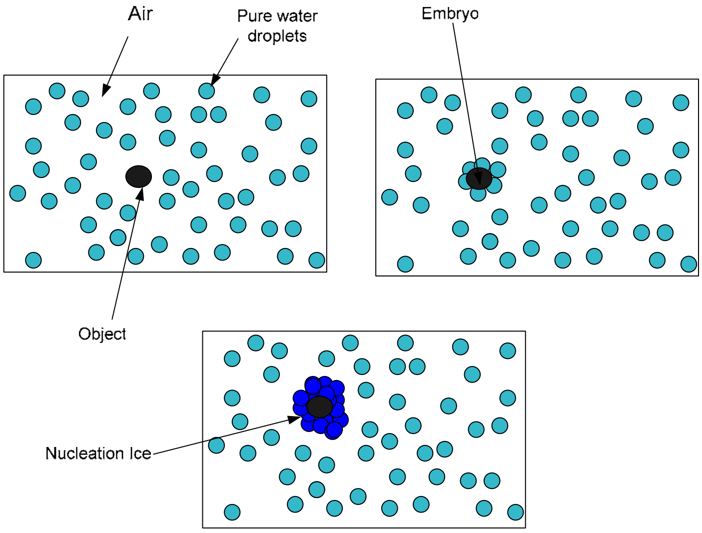

**Figure 8.13 Hetergeneous nucleation**

In the static filter the filter has high collection efficiency against both big and small particles from the beginning of its operation. That means that the air has high quality downstream the filter [15]. The water vapor in the air will not find its nucleus to crystallize to ice. Thus water vapors will have more time to condensate on the surface or/and freeze to super cooled water droplets. Moreover the smaller the droplets, the lowest the temperature is needed to convert the droplets to ice that's mean the water droplets will stay liquid. Both of these actions cause icing on the surface. In contrary pulse filter has low efficiency against small particles. These particles constitute nucleus for water vapors in the air. Thus water droplets will crystallize to ice crystals or/and ice fog with homogeneous nucleation in lower temperatures. Ice fog and ice crystals don't constitute hazard on the gas turbine. When the pulse filter pulses the dust cake on its elements so clean the air the holes which are between fibres. This lets the small particles go through the pulse filter and repeats the nucleation process.

## 8.6 System selection

While any of these systems can keep a gas turbine running through an arctic winter without problems, there are many considerations that have to be taken into account for making a right choice. The first factor is the application of the gas turbine. If the gas turbine is a part of a combined cycle the water heat exchanger is the most suitable and economical choice. Another factor is the system complexity, which relates to both power plant cost and reliability. The heat recovery anti-icing system is more complex than other systems which mean it's a costly alternative but it has less impact on the gas turbine performance. Thus economical study has to be done to select the best suitable anti-icing system for a certain application. After my studying to these systems I recommend using a conventional anti-icing system "Bleed compressor heating" with a static filter. This combination makes sure that the gas turbine is protected against ice formation hazards. Many manufacturers prefer to use pulse filter as an anti-icing system because it's a cheap solution and they don't have to have anti-icing system. I recommended using the pulse filter just for the function that it was made out for. In other words use it in the desert environment where the air is dry. Pulse filter as mentioned in chapter 7 has a main disadvantage which limits its profits. The pulse filter has low efficiency against small particles which is so difficult to pulse away from the filter media. Moreover pulse filter is inefficient under moist environment. Water and humidity make fine dust sticky. The pulse clean system cannot release this containment from the medium and the filter will not be cleaned. As a consequence the pressure drop will increase in the inlet system affecting the gas turbine output power. In addition there is no guarantee from pulse filter manufacturers that pulse filter system can ensure inlet system without ice.

For arctic environment I recommended to use static filter with anti-icing system because it gives high protection for the gas turbine from icing hazards.

## 8.7 System Comparison

The following table (8.1) shows a short summary of the different anti-icing /de-icing systems and a comparison between them.

| Ice protection system | Thermal system | | | | | |
|---|---|---|---|---|---|---|
| | Inlet heating system | | | | Components heating | |
| | **Compressor bleed inlet heating** | **Exhaust recirculation** | **Heat recovery** | **Hot water heat exchanger** | **Electrothermal** | **Compressor bleed air** |
| **Anti-/De-icing system** | Anti- | Anti- | Anti- | Anti- | Anti- | Anti- |
| **Concept** | Discharge a portion of the hot air from the compressor and mix it with cold ambient air. | Mixing a potion of the hot exhaust gases with the cold ambient inlet air. | Passing exhaust gases and air after the filter through a H.E. The heated air directs then to the GT intake to warm the incoming air to the GT. | The warm water enters a H.E and the ambient cold air enters the H.E with reverse direction. This warm up the incoming cold air. | Consists of resistance wires imbedded in rubber pads which are mounted on the icing surface that shall be protected. | Drilling canals in the icing components. The hot air passes through these canals and warms up these components. |
| **Advantages** | - Simple<br>- Using dry/ warm air<br>- Reliable & controllable<br>- Quick-acting<br>- Relatively least expensive | - Less effect on GT performance | - Using dry/ warm air<br>- Less effect on GT performance | - Simple<br>- Less effect on GT performance<br>- Relatively leas expensive | - Warms up just icing surface<br>- Needs less heat<br>- Little/no effect on GT performance | Warm up just icing surface<br>- Needs less heat<br>- Little/no effect on GT performance |
| **Disadvantages or limitations** | - Affect the GT performance.<br>- Most popular | - Exhaust gases contain many impurities<br>- Affect air humidity<br>- Exhaust gases low pressure | - Complex<br>- Expensive<br>- Bulky | - Not known | - Difficult to determine icing points<br>- Installations difficulties | - Installations difficulties<br>- Expensive |
| **Former applications** | - Simple cycle<br>- Peaking units | - Simple cycle<br>- Unfavorable | - Simple cycle | - Combined cycle | - Aero-engines | - Aero-engines |

| Ice protection system | Chemical system | Mechanical system | Inertial system (Inlet hoods) | Other systems | |
|---|---|---|---|---|---|
| | | | | **AMIS (H.E/ moisture separator)** | **Pulse jet filters** |
| **Anti-/De-icing system** | Anti- | De- | Anti- | Anti- | Anti- |
| **Concept** | Mixing liquid water with freezing point depressant. The freezing point of the resultant mixture will be lower than the freezing point of either constituent. | Manual brushing of hoarfrost from the filter. Electrical brushing systems can be used also. | Separation of particles from an air-stream that carries them. It achieves this by forcing the air stream to change its direction drastically. | AMIS system separates droplets from incoming air. Exhaust gases are drawn through the inside the H:X warming up the ambient cold air. | According to my theory: The pulse filter allows small particles at reach the compressor inlet. These particles can be nucleates to convert water to ice. |
| **Advantages** | - No effect on GT performance | - Clean the filter from frost | - Separates large ice particles (hail ect.)<br>- Separates dust and sand. | - Less effect on GT performance | - No effect of GT performance |
| **Disadvantages or limitations** | - Expensive<br>- Some anti-icing solutes are sticky | -Does not mitigate condensate icing in the GT inlet | - Does not mitigate condensate icing in the GT inlet | - Exhausts gases low pressure. | - Inefficient against small particles<br>- Cannot get rid of small particles<br>- Inefficient with humid air<br>- Expensive |
| **Former applications** | - Washing compressor in winters<br>- Simple cycle | - Simple and combined cycles | - Simple and combined cycles | - Simple cycle | - Simple cycle |

Table 8.1 Comparison between different anti- and de- icing systems

# 9. Icing Condition Regions

## 9.1 Introduction

To study the icing conditions of a gas turbine accurately two factors have to be taken into account; the recovery factor and the velocity of the air stream in the inlet to the compressor. These factors have a great influence on determination of the icing condition regions. To figure out if a certain ambient condition constitutes an icing hazard in the gas turbine two conditions have to be checked out. First is if the surface temperature is lower than the dew point temperature of the air in the intake system, the second factor is if the icing surface temperature is lower than freezing point temperature.

## 9.2 Icing condition regions calculations

The cold ambient air in front of the intake system of the gas turbine has the following dry composition. The ambient air dry composition is in table (9.1)

| **Standard Dry Air Composition** | | |
|---|---|---|
| ***Gas*** | ***Molecular Weight [Kg/Kmol]*** | ***% by Volume*** |
| Nitrogen [$N_2$] | 28,013 | 78,088 |
| Oxygen [$O_2$] | 31,999 | 20,949 |
| Carbon Dioxide [$CO_2$] | 44,010 | 0,930 |
| Argon [Ar] | 39,948 | 0 |
| Sulfide dioxide [$SO_2$] | 64,063 | 0 |
| Water [$H_{2O}$] | 18,015 | 0 |
| Helium [He] | 4,003 | 0 |

**Table 9.1 Air dry composition**

With calculations of icing conditions the wet air composition has to been taken into account. That means that the water content ω has to been considered and air composition for dry air has to be modified to give the wet air composition. The following equations explain the ambient air manners from the air intake system to the compressor inlet. In the end the icing condition regions for specific ambient conditions can be figured out.

The absolute humidity of the ambient air in front of the intake system is given by

$$\omega = 0,6236.\frac{\phi.P_{\upsilon,H2O}}{P_{o1} - \phi.P_{\upsilon,H2O}} \tag{9.1}$$

| | |
|---|---|
| ω: Absolute humidity of the ambient air in front of the intake system | [kg water/kg air] |
| $\phi$ : Relative humidity of the ambient air in front of the intake system | [%] |
| $P_{\upsilon, H2O}$: Partial pressure of the water at ambient temperature | [bar] |
| $P_{o1}$: Total pressure of the ambient air | [bar] |

The ambient air flow which moves toward the intake system experiences pressure drop. Thus the total air pressure in front of the compressor is

$$P_{o2} = P_{o1} - \Delta P \qquad (9.2)$$

$P_{o2}$: Total air pressure in front of the compressor [bar]
$P_{o1}$: Total air pressure in front of the intake system [bar]
$\Delta P$: Pressure drop in the intake system [bar]

The static pressure of the air in front of the compressor can be deified as

$$P_{s2} = P_{o2} - \frac{\rho . C_2^2}{2} \qquad (9.3)$$

$P_{s2}$: Static air pressure in front of the compressor [bar]
$\rho$: Air density in front of the compressor [kg/m$^3$]
$C_2$: Air velocity in front of the compressor [m/s]

The total air temperature is constant in the air flowing along air path from the inlet of the intake system to the inlet to the compressor because there is no heat or work transfer.

$$T_{o1} = T_{o2}$$

The total temperature can be rewritten as a combination of static temperature and dynamic temperature.

$$T_{s1} + \underbrace{\frac{C_1^2}{2.Cp_1}}_{=0} = T_{s2} + \frac{C_2^2}{2.Cp_2} \qquad (9.4)$$

$T_{s1}$: Static air temperature in front of the intake system [C$^o$]
$T_{s2}$: Static air temperature in front of the compressor [C$^o$]
$C_1$: Air velocity in front of the compressor [m/s]
$Cp_1$: Specific heat capacity of the air in front of the intake system [kJ/kg.K]
$Cp_2$: Specific heat capacity of the air in front of the compressor [kJ/kg.K]

The air velocity in front of the intake system is low relatively to the air velocity in front of the compressor hence velocity in front of the intake system can be assumed negligible. The static temperature depression as a result of air acceleration in the intake system can be calculated from the equation

$$\Delta T_s = T_{s1} - T_{s2} = \frac{C_2^2}{2.Cp_2} \qquad (9.5)$$

$\Delta T_s$: Static temperature depression in the intake system [C$^o$]

Thus the static temperature in front of the compressor will be

$$T_{s2} = T_{s1} - \Delta T \qquad [C^o]$$

It is possible to calculate surface temperature which is the first condition in the determination of icing conditions. To calculate the surface temperature, the recovery factor which has been discussed in chapter 7 has to been used. From the recovery factor definition the surface temperature can be given as

$$RF = \frac{T_{surface} - T_{static}}{T_{total} - T_{static}} \tag{9.6}$$

RF: Recovery Factor [-]
$T_{surface}$: Surface temperature of the icing surface [C°]
$T_{static}$: Static temperature of the air in front of the compressor [C°]
$T_{total}$: Total temperature of the air [C°]

The recovery factor is individual for each gas turbine which means that each gas turbine has a specific value. This because of each gas turbine has its own construction and design which means the surface temperature differs from turbine to other turbine. To decide the recovery factor for a gas turbine the icing surfaces temperatures have to been measured. Icing surfaces are surfaces where ice is likely to build up. Icing surfaces can be plenum, bellmouth, struts and IGVs. It wasn't possible under my master thesis period to do the surface temperature measurements for the intake system components. So I took the theoretical value of the recovery factor in my calculations which is 0, 8. However I recommended doing the measurements of surface temperature because the recovery factor is a basic factor in the determination the icing conditions for a gas turbine. Thus the surface temperature is

$$T_{surface} = T_{s2} + RF.\,(T_{o2} - T_{s2}) \quad [C^o] \tag{9.7}$$

The second condition on determination the icing condition is deciding if the icing surface is temperature lower than dew point temperature of the air in the intake system. The dew point of the air in front of the compressor is not equal to the dew point of the air in front of the inlet system.
The dew point temperature is given by

$$T_{dp} = T_{saturated@P_{\upsilon H2O}} \quad [C^o] \tag{9.8}$$

$T_{dp}$: Dew point temperature of the air [C°]
$P_{\upsilon,\,H2O}$: Partial pressure of the water [bar]

The partial pressure in the intake system can be obtained by

$$P_{\upsilon H2O} = \upsilon_{H2O}.P_{s2} \quad [bar] \tag{9.9}$$

$\upsilon_{H2O}$: Volume fraction of water in the air [-]
$P_{s2}$: Static pressure of the air in front of the compressor [bar]

The ambient air accelerates from the inlet of the intake system to the inlet of the compressor. This leads to static pressure depression, and following depression in partial pressure of the water. Therefore the dew point of the air will also experience depression.

By knowing the partial pressure of the air in the intake system the relative humidity of the air will be

$$\phi = \frac{P_{\upsilon,H2O}}{P_{\upsilon\,\text{saturated@t2}}} \qquad [\%] \qquad (9.10)$$

To decide if these ambient conditions constitute ice hazard in the gas turbine, two conditions have to be accomplished

1. The surface temperature has to be lower than the dew point temperature of the air in the intake system. As a result water vapor will condense from the air to the surface, $T_{surface} < T_{dp}$.
2. The surface temperature is below freezing point temperature. Therefore water which has condensed on the surface will solidify and build ice, $Tsurface \leq 0$ [31, 32].

As long as the surface temperature is above the water saturation temperature, condensation will not occur and ice will not form even if the surface temperature is below freezing point temperature [31,32]. There are other combinations between these conditions. The results depend upon the gas turbine designs and operating conditions. If the relative humidity of the air in front of the compressor is at or near the saturation point *fog* is likely to occur. With combination of very low static air temperature in front of the compressor, below -30 $C^o$, the water droplets in the air will crystallize and be as known *Ice Fog. Ice crystals* conditions differ from ice fog in the way that air doesn't reach the saturation point of water in the air, in other words the relative humidity of the air is less than 100 %. The choice of -30 [$C^o$] as a design point where ice fog and ice crystals form in the air, depends upon metrology information. The formation and ingestion of ice crystals or/and ice fog don't constitute hazard to the compressor. At the contrary, if surface temperature drops below the dew point temperature of the air in front of the compressor the condensation will take place on the surface. With surface temperature lower than freezing point temperature the ice will begin to grow on the surface. There are two types of ice that can be seen on the surface as a result of condensation; rime ice and glaze ice. The only difference between them is the surface temperature at which they form. My surface temperatures selections for glaze ice and rime ice formation are based on aircraft engines experience from icing and on metrology information. For glaze ice, it wasn't easy to decide the exact surface temperature range where glaze ice can form. From Metrology perspective in the reference [48] glaze ice can build up when surface temperature lie between 0[$C^o$], to -9 [$C^o$], in other hand reference [6] believes that glaze ice can form with surface temperature as low as -15 [$C^o$]. Aircraft engines experience from icing shows that glaze ice occurs at surface the temperature range of 0 [$C^o$] to -10 [$C^o$]. In my calculations I took the worst case as a design point for glaze ice formation and I designed with surface temperature range between 0 [$C^o$] and -15 [$C^o$]. Metrology assumes that rime ice can be formed at temperatures as low as -22 [$C^o$]. But aircraft icing researches show that rime ice can occur with temperature as low as -30 [$C^o$]. It is apparent that rime ice begins to appear in the place where glaze ice conditions close its limits. Glaze ice and rime ice are both ice types that result from condensation, so rime ice begins where glaze ice ends. The frost looks like the rime ice but it is formed by direct sublimation from water vapor in the air to solid ice on the surface. Frost occurs when the air is saturated and surface temperature is at or lower than the freezing point temperature and static air temperature in front of the compressor is higher than -30 [$C^o$] . When the static air temperature in front of the compressor is lower than -30 [$C^o$], water vapor in the air will crystallize quickly, which gives ice fog. The free moisture region is the case when the air in the intake system is unsaturated. The air can contain water vapor, supercooled water droplets and ice crystals depending on air temperature in front of the compressor. The glaze ice is the ice type which constitutes the greatest hazard to the compressor. It's difficult to recognize it when it forms in the inlet system because it's transparent.

The ambient air accelerates from low velocity in front of the intake system to high velocity in front of the compressor. Thus static air temperature depression differs from point to point in the inlet system. As a consequence, icing can occur in different places in the intake system depending on the air velocity in the intake system. It's more convincing and methodic to examine various icing conditions at different velocities in the intake system and then decide the critical place. The icing conditions for gas turbine are examined for different ambient air conditions and the calculations begin at low velocity in the order of 50 [m/s] and end at very high velocity in order of 270 [m/s]. The figures from(1) to (15) demonstrate icing conditions region for ambient air temperatures from -40 $C^o$ to 10 $C^o$ and relative humidity from 0% to 100 %. These calculations are based on the previous introduction.

## 9.3 Results

I. $V_2 = 50$ [m/s]

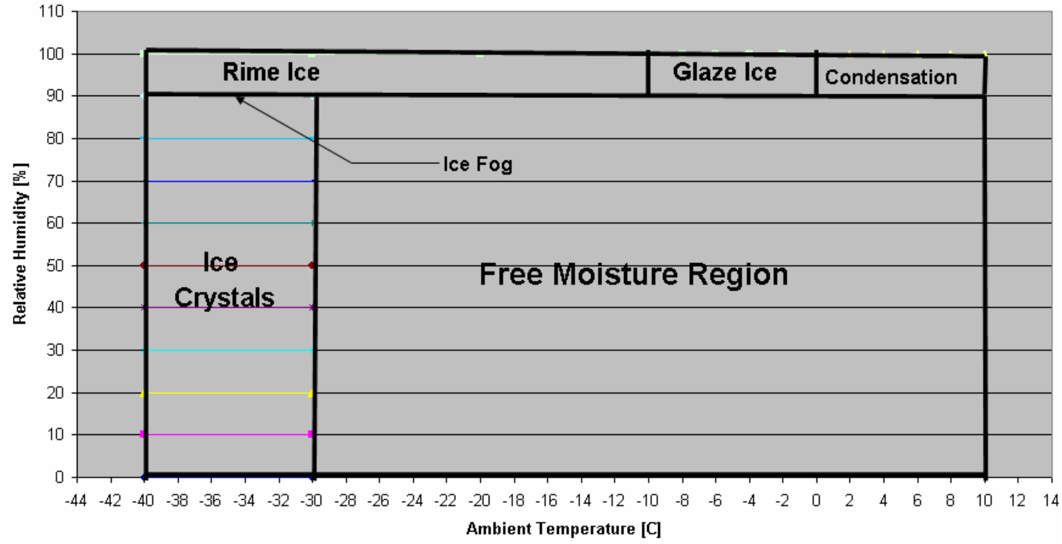

**Figure 9.1 Icing Conditions Region, $V_2$= 50 [m/s]**

From the (Fig. 9.1), it's clear that air velocity in the intake system is low enough so that the air doesn't reach its saturated point until ambient relative humidity reaches 90%. Ice crystals begin to take place when the ambient air temperature is lower than -30[C$^o$]. Ice fog as a consequence begins to occur from air relative humidity 90% and ambient air temperature lower than – 30 [C$^o$]. It's apparent that the free moisture region is what usually occurs under ambient conditions combinations. Condensation begins with ambient relative humidity higher than 90 % and surface temperature below air dew point temperature in the intake system. Glaze ice, which is the design condition of our anti-icing system, builds up on the surface at ambient air temperatures between -10 [C$^o$] and 0 [C$^o$] and air relative humidity more than 90 %.While rime ice builds up at ambient air temperature lower than -10 [C$^o$]. To obtain a more accurate image of glaze ice region conditions, the calculations of icing conditions region can be done for relative humidity between 90% and 100% (Fig. 9.2)

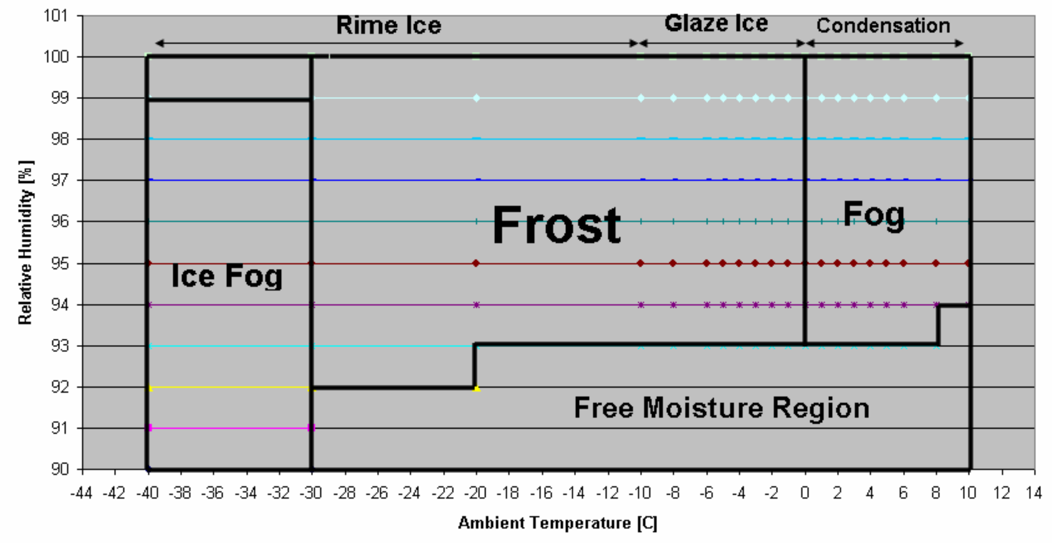

**Figure 9.2 Icing Conditions Region, $V_2$= 50 [m/s]**

(Fig. 9.12) gives a better image of icing regions for relative humidity above 90 %. Frost and fog begin to form at relative humidity above 92%. The most important region here is the glaze ice region which occurs with very high relative humidity at 100% and temperatures between -10 [$C^o$] and 0 [$C^o$]. Rime ice begins to occur with relative humidity 98% and temperatures between -10 [$C^o$] and -40 [$C^o$]. It's apparent that the low air velocity leads to small temperature depression in the intake system. Thus ice possibility is little here.

To find the critical point in the intake system more velocities have to be taken in concern. As the air moves towards the inlet of the compressor the velocity of the air increases continuously until it reaches its peak value at 270 [m/s] for SGT-700. The icing conditions calculations have been done for the following velocities 80, 130, 150, 180, 200, 250 and 270 [m/s] and the icing conditions regions have been figured out.

II. $V_2 = 80$ [m/s]

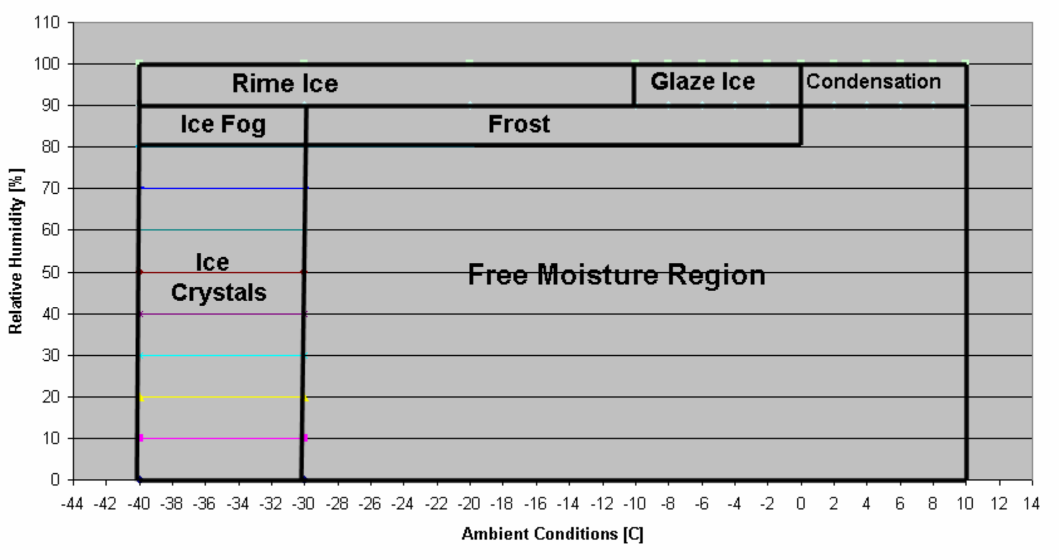

**Figure 9.3 Icing Conditions Region, $V_2$= 80 [m/s]**

At air velocity 80 [m/s] the icing condition regions don't experience great changes. Free moisture region is still the biggest region between other regions because the air velocity didn't reach the values which allow the air to be saturated. The only difference between 50 and 80 [m/s] is that the frost and ice fog regions begin to be clear. Rime ice and glaze occur with ambient air relative humidity above 90%

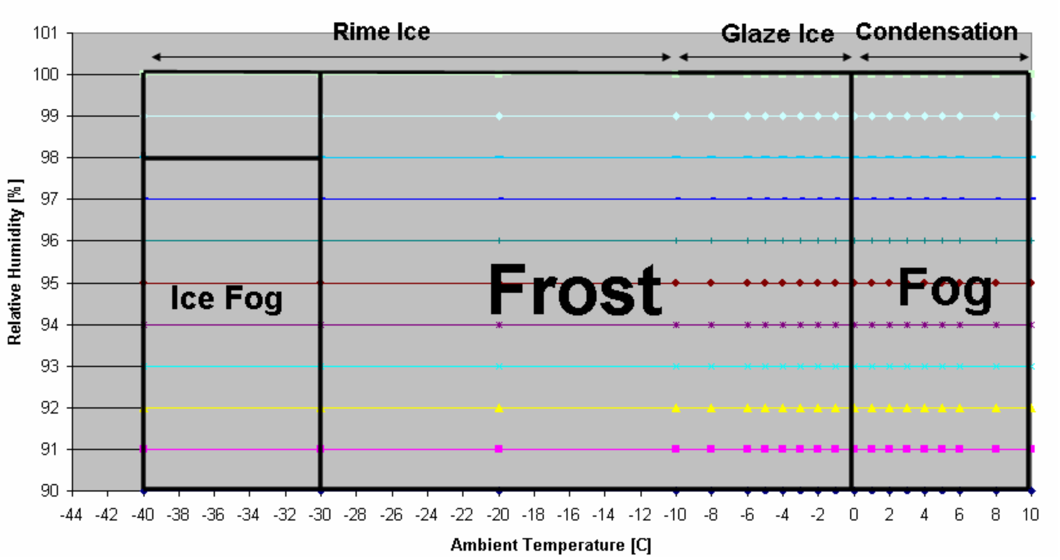

**Figure 9.4 Icing Conditions Region, $V_2$= 80 [m/s]**

As we notice from the (Fig. 9.4) icing condition regions at velocity 80 [m/s] are the same at air velocity 50 [m/s]. Glaze ice region appears when ambient air temperature is between -10 [C$^o$] and 0 [C$^o$] and ambient air relative humidity is 100%.

II. $V_2$ = 130 [m/s]

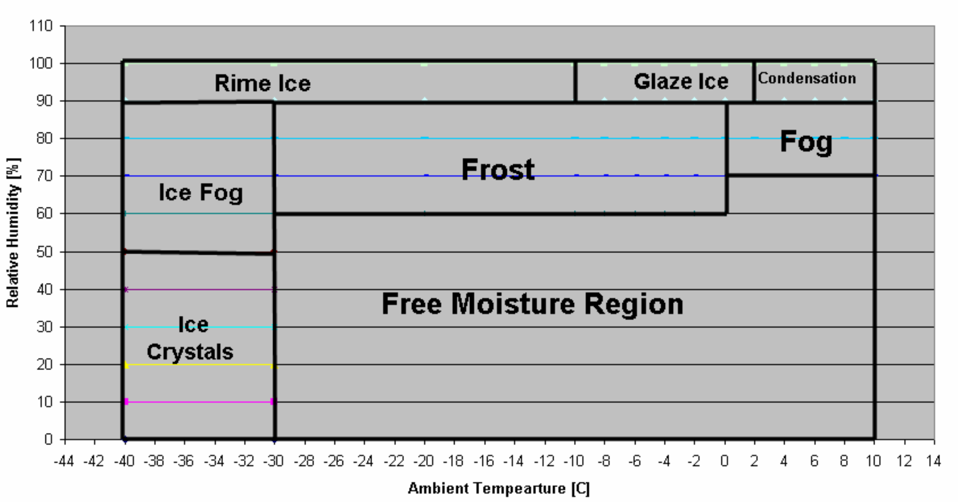

**Figure 9.5 Icing Conditions Region, $V_2$= 130 [m/s]**

When the air reaches the point in the inlet system where its velocity is 130 [m/s], the temperature depression in the inlet system increases and as a result the static air temperature decreases. Therefore we can notice that frost and ice fog regions begin to be more obvious. Ice crystals still occur with ambient air temperatures below -30 [C$^o$]. The free moisture region diminishes because of increasing relative humidity of the air in the inlet system. Also the calculations has to be done again for relative humidity above 90% here to get clearer image of glaze ice region (Fig. 9.6)

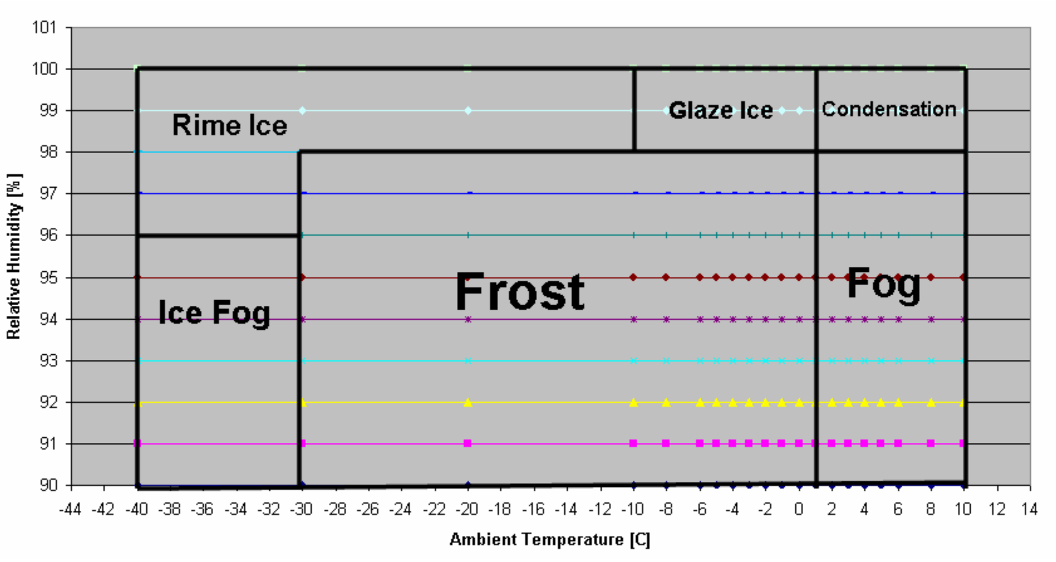

**Figure 9.6 Icing Conditions Region, $V_2$= 130 [m/s]**

Glaze ice region occurs with air velocity 130 [m/s] at higher ambient air temperature than when air velocity is 50 [m/s]. From the (Fig. 9.6) it is seen that glaze ice region lies in ambient air temperatures between 1[C$^o$] and -10 [C$^o$]. In other hand rime ice begins to occur with relative air humidity above 96 %.

III. $V_2$ = 150 [m/s]

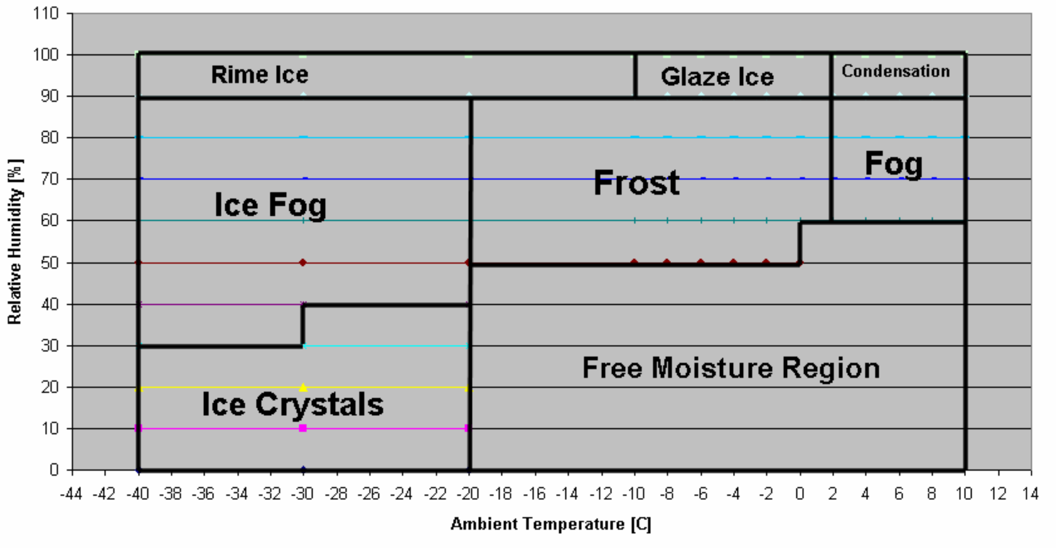

**Figure 9.7 Icing Conditions Region, $V_2$= 150 [m/s]**

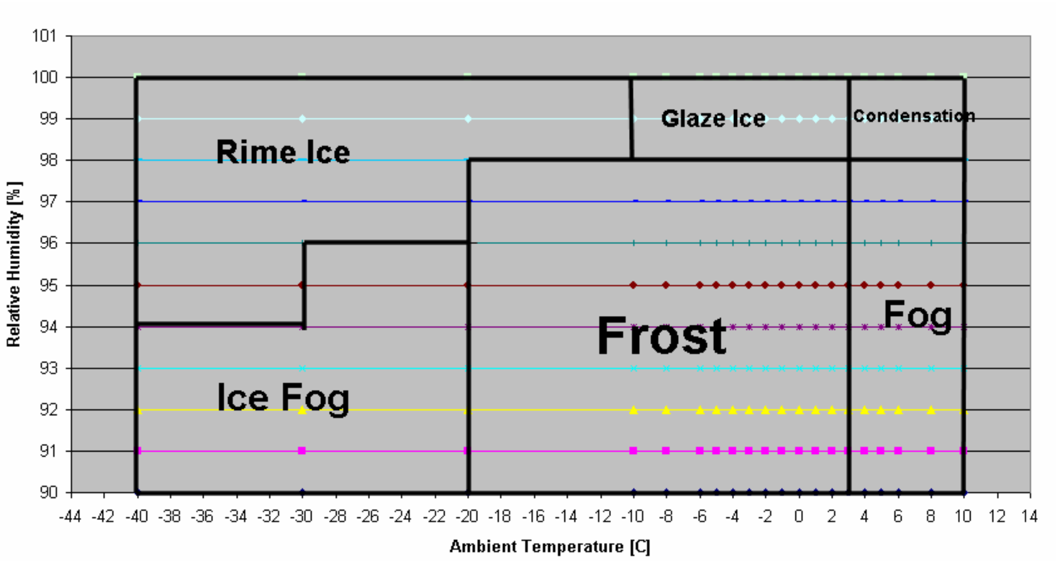

**Figure 9.8 Icing Conditions Region, $V_2$= 150 [m/s]**

From (Fig. 9.8), it's apparent that ice begins to form with all its types under a wider range of ambient air conditions. Ice fog occurs with ambient air temperature below -20 [C$^o$] and low relative humidity 30%. Fog region as well occurs more clearly in the icing regions. This can be explained by when the air velocity increases in the inlet system, the temperature depression increases. As a consequence the air will be saturated easier and therefore ice fog and fog expand their regions. The rime ice region has wider icing conditions because of increased condensation. It rises when the ambient air temperature is between 3 [C$^o$] and -10 [C$^o$] and the relative humidity is at or above 98%. In the other hand rime ice region begins to occur when the glaze ice region ends but with lower relative humidity, at 94 %.

IV. 180 [m/s]

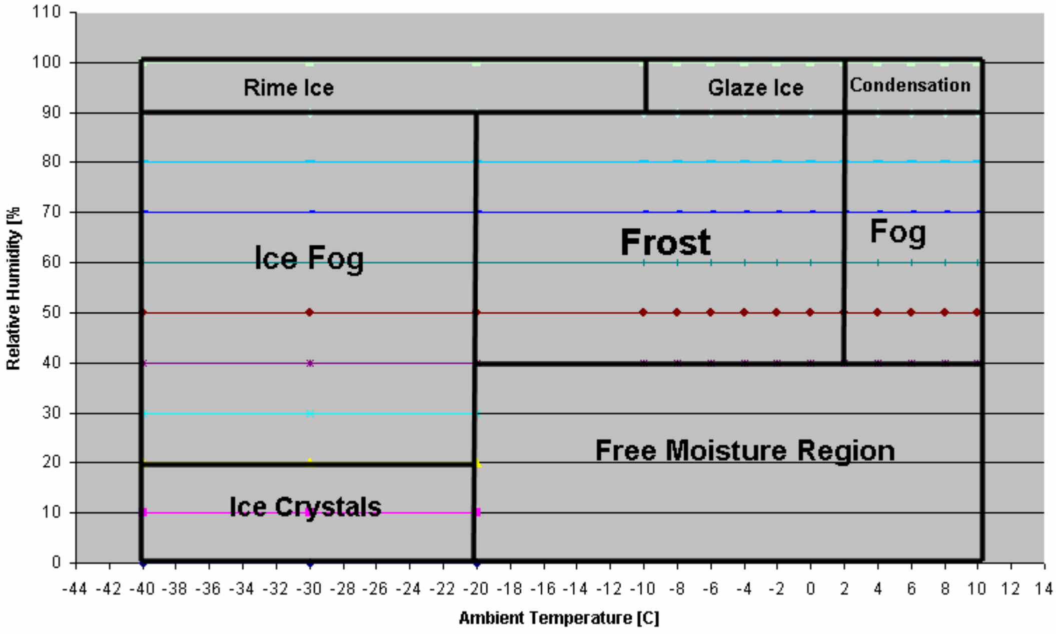

**Figure 9.9 Icing Conditions Region, $V_2$= 180 [m/s]**

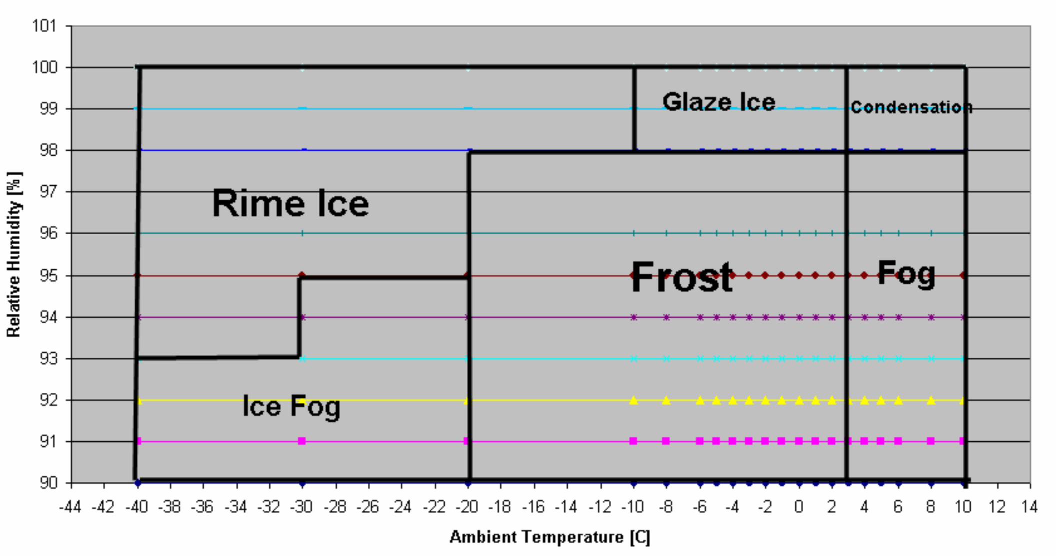

**Figure 9.10 Icing Conditions Region, $V_2$= 180 [m/s]**

The air velocity will continue to increase as air moves towards the compressor inlet. From (Fig. 9.10) we can notice that the icing conditions region begins to change in other ways. The ice crystals region decreases with increasing ice fog region and frost and fog regions increase with decreasing free moisture region. The explanation is that because of decreasing the static air temperature in the inlet system the air tends to be saturated at air conditions in the inlet system. Because of decreasing air the maximum water vapour capacity of the air. Glaze ice, which is the design case for our anti-icing system, occurs when the ambient air temperature is between 3[C$^o$] and -10 [C$^o$] and relative humidity at or above 98% while rime ice occurs with lower relative humidity 93%.

V. 200 [m/s]

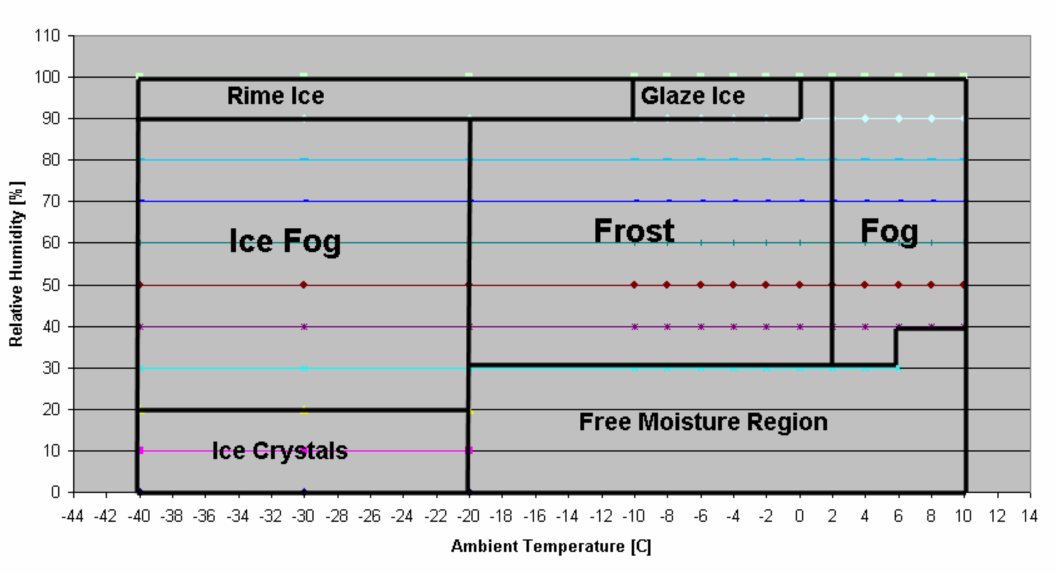

**Figure 9.13 Icing Conditions Region, $V_2$= 200 [m/s]**

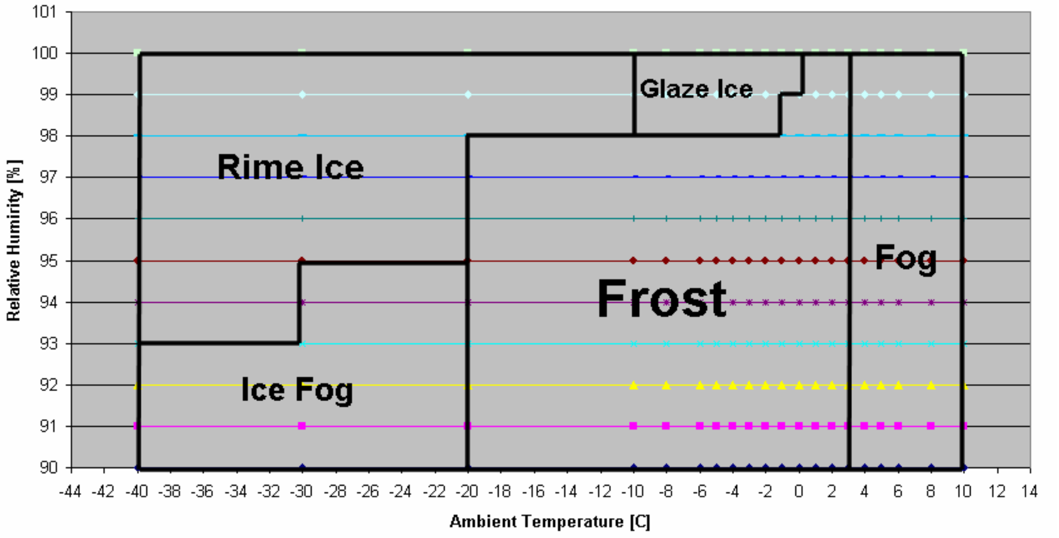

**Figure 9.14 Icing Conditions Region, $V_2$= 200 [m/s]**

The most important observation when the air velocity reaches 200 [m/s] is that the glaze ice region begins to diminish. This is of course because of increasing temperature depression in the inlet system. Glaze ice region occurs when the ambient air temperature is between 0 [C$^o$] and -10 [C$^o$] and relative humidity at or above 98%. Frost and ice fog regions continue to increase with decreased free moisture region.

VI. 250 [m/s]

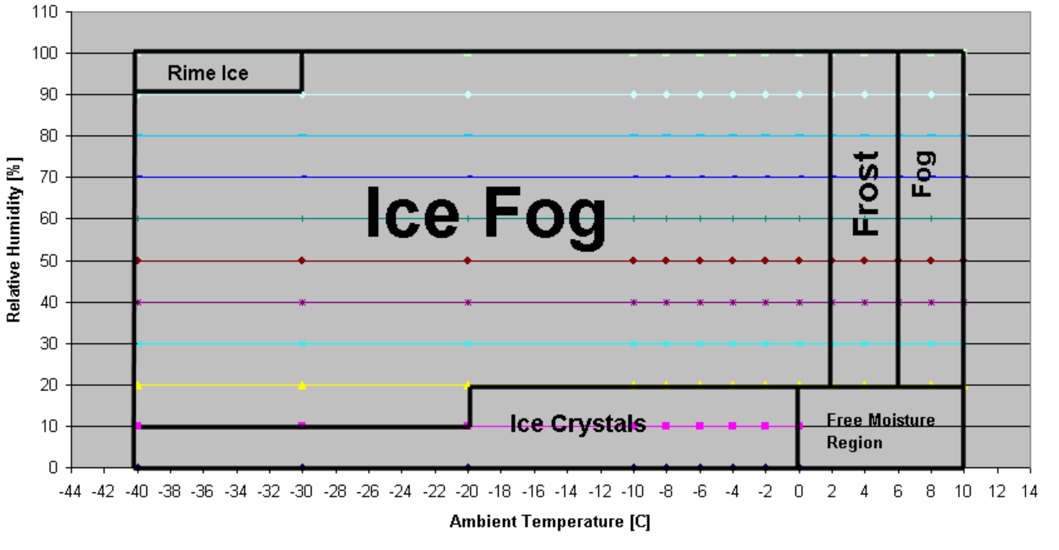

**Figure 9.15 Icing Conditions Region, $V_2$= 250 [m/s]**

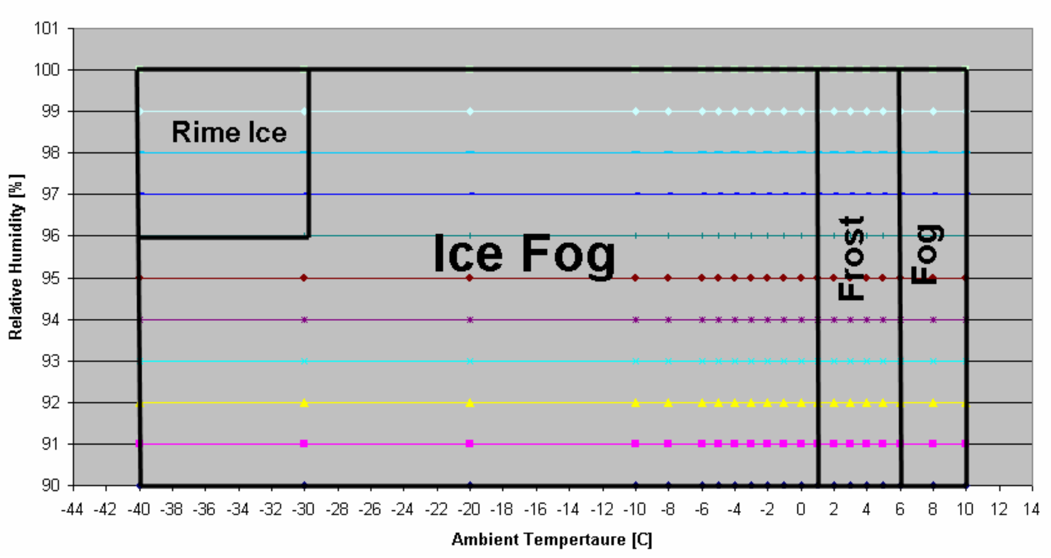

Figure 9.16 Icing Conditions Region, $V_2$= 250 [m/s]

As the air velocity in the inlet system reaches very high values, the icing conditions regions begin to change in a dramatic way. Because of the very high velocity of the air the temperature depression in the inlet system will be great and as a result the static temperature will be very low. This leads the air in the inlet system to reach to saturated point which gives fog, and crystallizes the water vapor in the air because of the air low temperature which gives ice fog. But an amount of water vapor in the air will also give frost. The most important conclusion from (Fig. 9.16) is that the glaze ice region hasn't appeared with this very high velocity. Rime ice region becomes smaller and arises with lower ambient air temperature -30 [C$^o$].

VII. 270 [m/s]

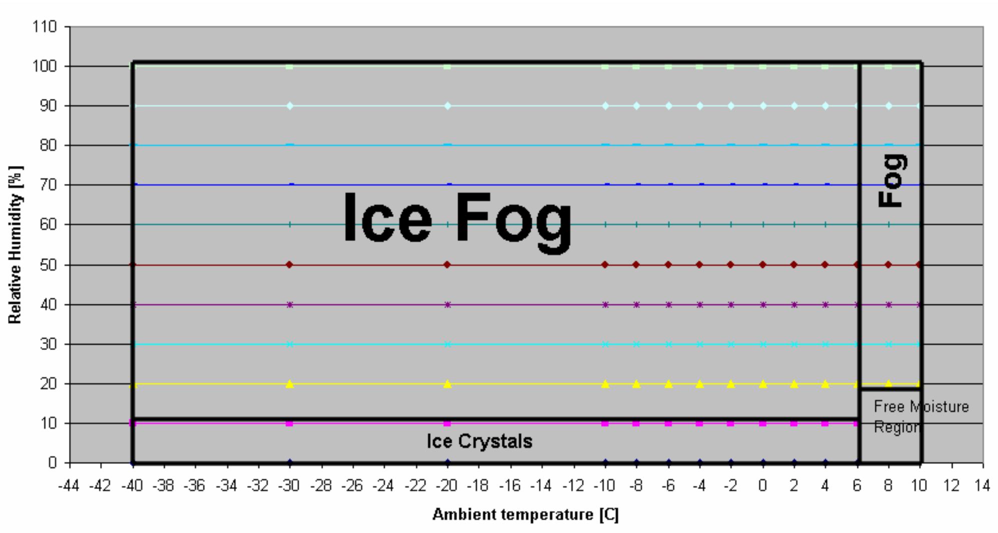

Figure 9.17 Icing Conditions Region, $V_2$= 270 [m/s]

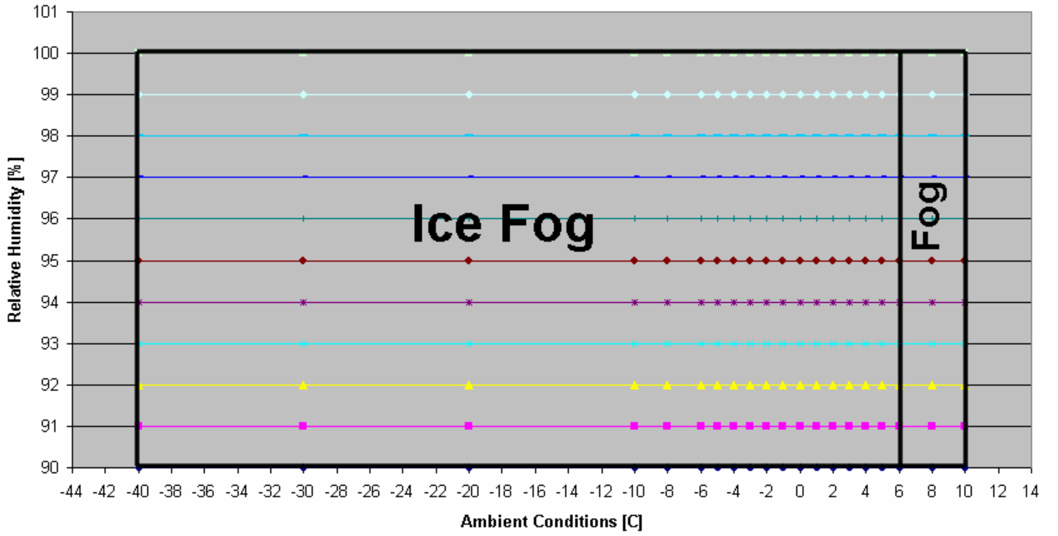

**Figure 9.18 Icing Conditions Region, $V_2$= 270 [m/s]**

As the air reaches its peak velocity 270 [m/s], the air temperature depression increases to a very high value in order of 30 [$C^o$]. That means that the static air temperature in front of the compressor is in the range of -30 [$C^o$] to -70 [$C^o$]. This leads to that the water vapor in the air will crystallize direct to ice and since the air is saturated ice fog will be the result. It's apparent from the figures (9) and (10) that ice fog takes up the whole icing conditions region. Glaze ice, rime ice, frost and ice crystals haven't appear with this very high air velocity. Only fog can appear in ambient temperatures above 6 [$C^o$].

It's apparent that the velocity of the air in the inlet system has a great effect on deciding the icing conditions under many combinations of ambient air conditions. A very important conclusion can be taken from figures that icing conditions regions change with increasing the velocity from 50 [m/s] to 270 [m/s] significantly. The glaze ice region which is the most important among others increases from 50 [m/s] to a limit where its region reach its maximal size when the air velocities are 150-180 [m/s], and then reduces with increasing velocity until this region disappear at 270 [m/s]. From (Fig. 9.9, 9.10) it can be noticed that at the air velocity 180 [m/s] the icing conditions regions begin to change its form toward decreasing glaze ice region. We can conclude also that the critical region for icing isn't where the velocity is highest but its lie close to air velocity 150 [m/s]. When designing the anti-icing system, the worst conditions must be taken in account to ensure that the turbine will work without problems. The critical conditions coincide with the velocity 150-180 [m/s].

## 9.4 Comparison with other gas turbine designs

Another gas turbine manufactures have designed icing conditions for their gas turbines. One of them is General Electric. General electric recommended to activate the anti-icing system when the temperature fall below 40 F (4, 4 C$^o$) in combination with relative humidity greater than 70 %. The icing conditions from General Electric demonstrates in (Fig. 9.19) [42]

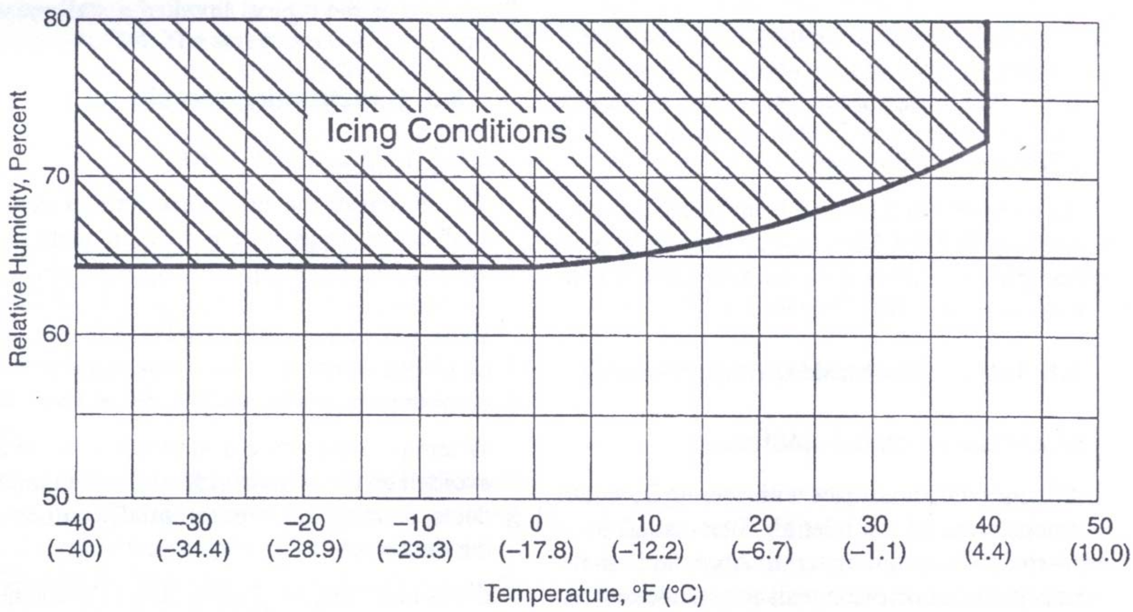

**Figure 9.19 GE icing conditions [42]**

It’s clear from the (Fig. 9.19) that General Electric activates the anti-icing system even when the ambient air temperature is very low -40 [C$^o$]. I don’t agree with this because through my understanding of the ice physics, all water vapor in the air will sublimate to ice direct when the air temperature is -40 [C$^o$] . It’s also not clear from which air velocity in the inlet system General Electric icing conditions have been gotten.

# 10. Performance Calculation

## 10.1 Introduction

After deciding the icing conditions regions at different velocities of the air in the intake system, the next step will be to decide how much we have to warm up the inlet air to avoid the ice on the inlet system components. As the determination of icing conditions regions showed, glaze ice region is the region which constitutes hazard to the gas turbine. Thus the designing of anti-icing system will be based on glaze ice region icing conditions.

To avoid ice formation on the intake system, it seems in the beginning that we have to keep the surface temperature above the freezing point temperature. But the deeper understanding to the icing mechanism shows that it is only necessary to heat the air enough to keep the surface temperature above the dew point temperature of the air in the inlet system. It is clearly that it will generally require less heat than it is required to keep the surface temperature above 0 $C^o$ [31, 32]. The glaze ice region icing conditions are defined by a combination of ambient air temperature and relative humidity. We have concluded from icing conditions calculations that glaze ice region which coincides with air velocity 150 [m/s] is the design because of it has the widest icing conditions. This region exists between ambient air temperatures from -10 $C^o$ to 3 $C^o$ and relative air humidity at or above 98 %. However, to figure out the maximal heat requirement to avoid ice building on the surface the calculations will be done for in all air velocities where glaze ice is present 50, 80, 130, 150, 180 and 200 [m/s].

## 10.2 Siemens gas turbines heat power for anti-icing system

The master thesis covers two Siemens gas turbines anti-icing systems, SGT 700 and SGT 800. For SGT 700 a compressors bleed anti-icing system has been studied while SGT 800 uses water heat exchanger as an anti-icing system. However, SGT 700 uses a water heat exchanger as a standard anti-icing system. In this thesis, however, we chose to study the compressors bleed anti-icing system for SGT 700 and the water heat exchanger for SGT 800 to include both systems in our study.

### *10.2.1 SGT-700*

The Siemens SGT-700 Industrial gas turbine (formerly known as the GT10C) is an updated version of the proven SGT-600 (formerly known as the GT10B) (Fig. 10.1). The SGT-700 is a twin-shaft machine with 11 compressor stages. The first two stages have variable inlet guide vanes. Table (10.1) shows SGT-700 characteristics.

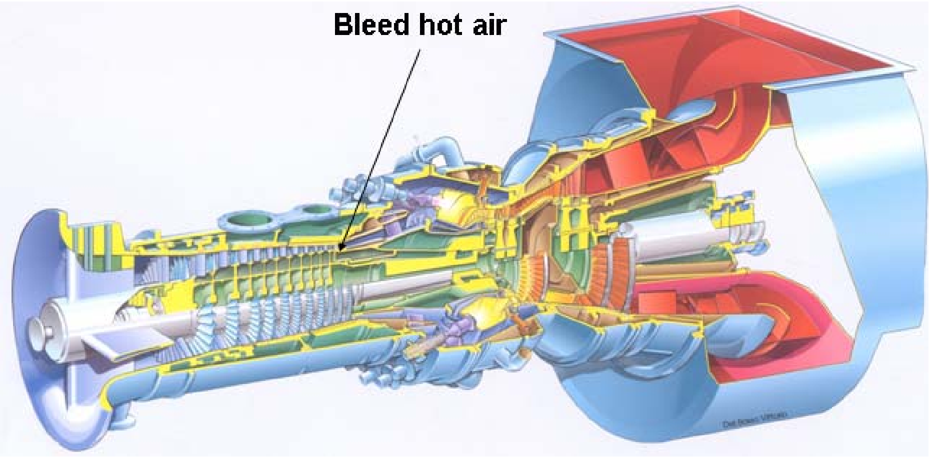

**Figure 10.1 SGT-700 [85]**

| | Power Generation | Mechanical Drive |
|---|---|---|
| **Output [MW]** | 29,060 | 30,10 |
| **Electrical efficiency [%]** | 36 | 37.3 |
| **Compressor pressure ratio** | 18:1 | 18:1 |
| **Power turbine speed [rpm]** | 6500 | 6500 |

**Table 1 SGT-700 characteristics [85]**

SGT 700 is a gas turbine applied sometimes in simple cycles. In such cases when the turbine operates in arctic environments the SGT 700 sometimes use compressor heating system as an anti-icing system. The hot air is extracted from the last stage of the compressor and blends with cold ambient air in the inlet of the intake system (Fig. 10.2). From the theory we decided to heat the intake air to keep the surface temperature above the dew point temperature of the air in the inlet system. Thus we have to heat the ambient air inasmuch as ΔT.

$$\Delta T = T_{dew\ point} - T_{surface} \qquad [C^o] \qquad (10.1)$$

$\Delta T$: Equivalent temperature increase [$C^o$]

$T_{dew\ point}$: Dew point temperature of the air in the inlet system [$C^o$]

$T_{surface}$: Icing Surface temperature [$C^o$]

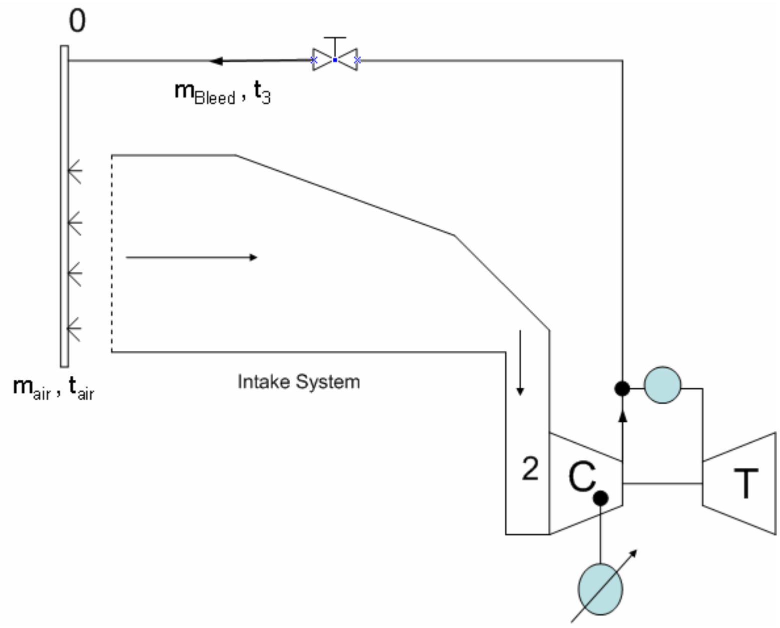

**Figure 10.2 Compressor inlets bleed system**

The heat power, which we get from the gas turbine after activating the anti-icing system to warming up the incoming air to the intake system, is given in equation

$$Q_{Bleed} = m_{air} \,.\, \text{extraction percent} \,.\, (h_3 - h_o) \qquad [kW] \qquad (10.2)$$

$Q_{Bleed}$: The amount of heat which is required to avoid ice formation [kW]
$m_{air}$: Air mass flow in the inlet of the intake system [kg/sec]
Extraction percent: The percent of hot air mass flow that extracts from the main flow in the compressor [%]
$h_3$: The extracted hot air enthalpy [kJ/kg]
$h_o$: The ambient air enthalpy [kJ/kg]

The enthalpy of ambient air can be taken from:

$$h_o = f\,(t_o, \text{Air composition}) \qquad [kJ/kg] \qquad (10.3)$$

$t_o$: Ambient air temperature [C°]

The enthalpy of the extracted hot air from the compressor is

$$h_3 = f\,(t_3, \text{Air composition}) \qquad [kJ/kg] \qquad (10.4)$$

$t_3$: Extracted hot air temperature [C°] (10.5)

The amount of heat that has to be extracted from the compressor to raise the incoming air to the gas turbine as much as ΔT decides the extraction percent. ΔT is the difference between the surface temperature and the dew point temperature of the air in the inlet system. We estimate a primary value of the extraction percent and then we check if this estimation gives at

$\Delta t = \Delta T$

Where $\Delta t$ is
$\Delta t = t_2 - t_o$ [C°]

$\Delta t$ :The temperature rise of incoming air to the intake system as a result of mixing ambient air with extracted the hot air from the compressor [C°]

$t_2$: Air temperature to the compressor inlet [C°]

$t_o$: Ambient air temperature [C°]

The temperature in the intake system of the gas turbine is
$t_2 = f\,(h2, \text{Air composition})$ [C°] (10.6)

The enthalpy in the intake system is a mix between the extracted hot air from the compressor and the ambient air (Fig. 10.3). It can be calculated from

$h_2 = (1 - \text{extraction percent}).h_o + \text{extraction percent}.h_3$ [kJ/kg] (10.7)

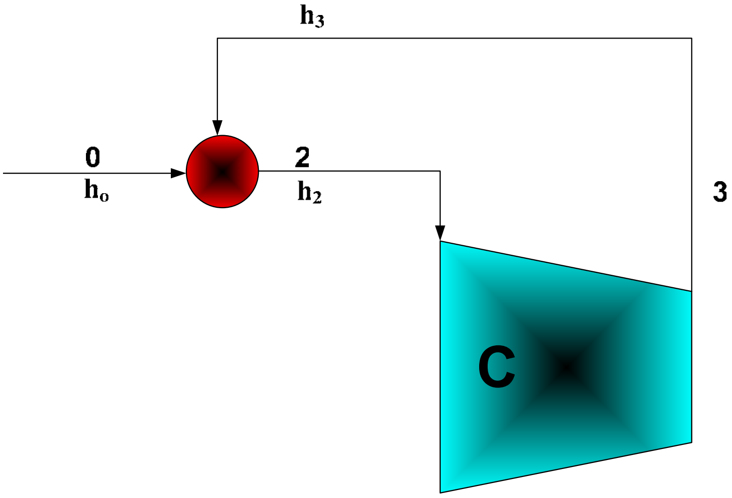

**Figure 10.3 Extracted hot air from the compressor**

To solve eq. 10.2 and get the enthalpy in compressor inlet, several iterations have to be done. In other words we estimate a value for the extraction percentage and if it doesn't fulfill the condition we recalculate for another extraction percent until we get $\Delta t = \Delta T$.

Then we replace the right value of the extraction percent and get the heat power $Q_{Bleed}$.

The mass flow of the extraction air from the compressor can be calculated from the equation

$m_{Bleed} = m_{air}. \text{Extraction percent}$ [kg/s] (10.8)

To do these calculations I used two programs which were my help tools, an internal program in Siemens which is called GT Performan and Microsoft Execl. These calculations have been done for all velocities where glaze ice icing conditions is present. The air velocities which coincide with glaze ice begin from low velocities in the order of 50 [m/s] to the highest velocity of 200 [m/s].

A safety factor (S) has been considered under the determination of the requirement heat effect. This Safety Factor includes two components. The first one is added to the dew point temperature of the static air in the inlet system to ensure that the calculations ice regions covers the whole icing conditions. This recover factor has been taken 0, 8 in the calculations. The other safety factor has been taken under the calculation of the heat power to ensure that the added heat is enough to avoid ice formation. This safety factor has been added to the temperature rise Δt at the inlet for the purpose to see how the heat power changes with increasing Δt. This safety factor has been done for three safety factors; 0, 2 and 4 [C$^o$]

The results are illustrated in figure (1) to (14). Theses figures cover velocities 50, 80, 130, 150, 180 and 200 [m/s]. For velocities above 200 [m/s] the glaze ice region hasn't been noticed. Thus above this velocity it's not necessary to worry about icing in the inlet system. Each velocity has three figures which present the results with one safety factor each. The figures consist of two y axes. This gives a combination of the ambient temperatures and the heat power and the ambient temperatures with inlet temperature increasing for different ambient relative humilities.

### 10.2.1.1 Heat power

*I.* $V_2$= 50 [m/s]

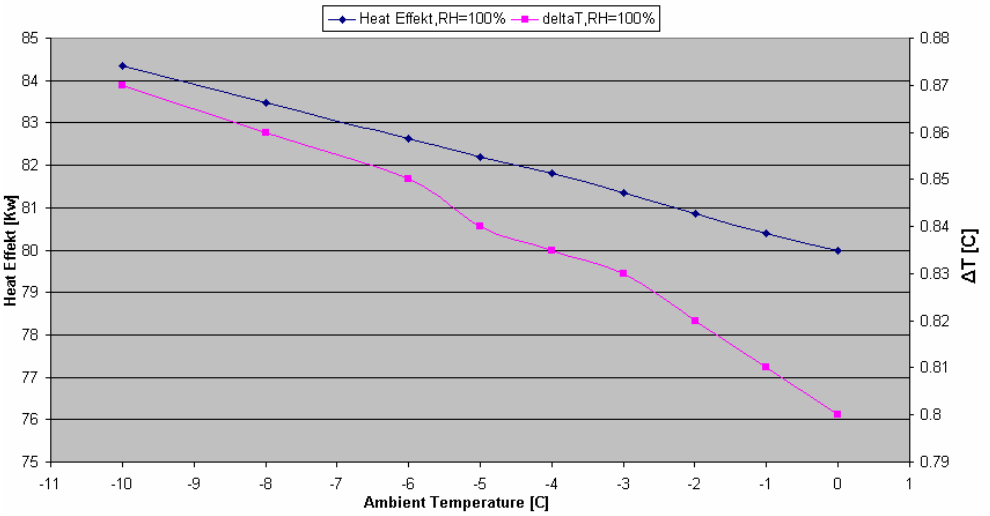

**Figure 10.4 $V_2$=50 [m/s], S=0**

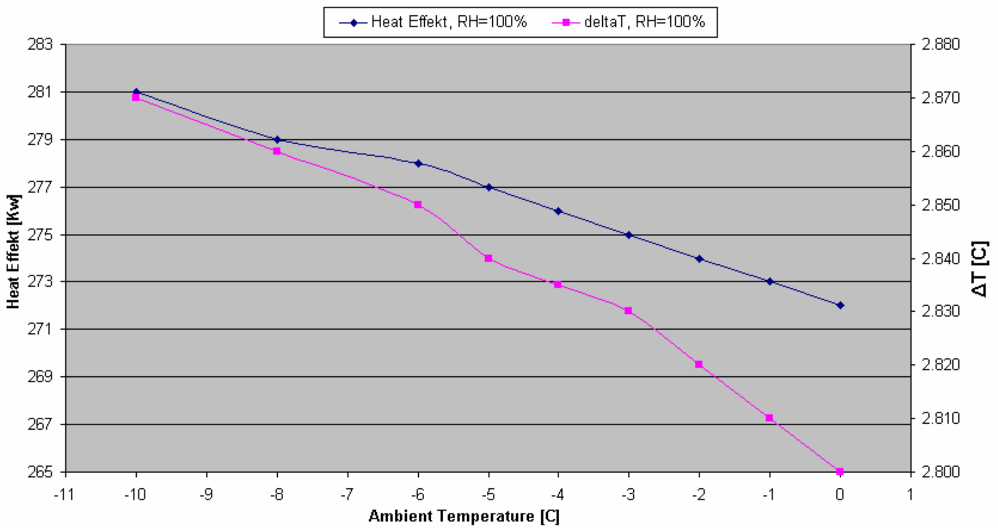

**Figure 10.5 $V_2$=50 [m/s], S=2**

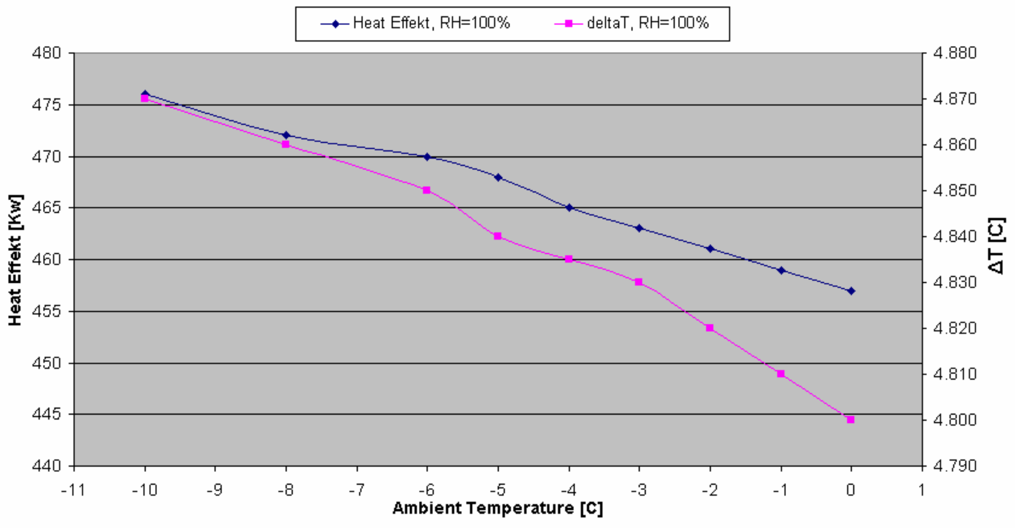

**Figure 10.6** $V_2=50$ **[m/s], S=4**

*II.* $V_2= 80$ [m/s]

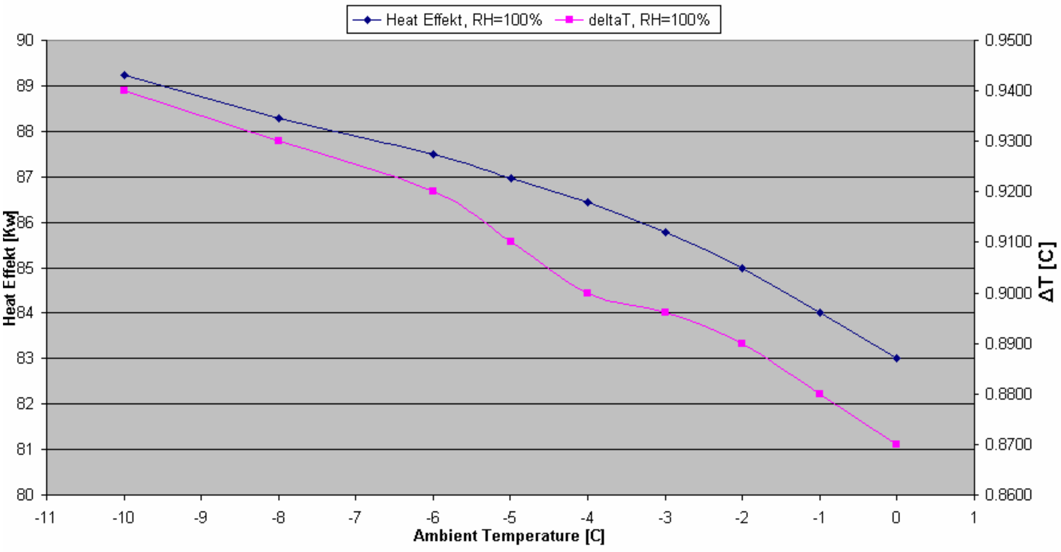

**Figure 10.7** $V_2=80$ **[m/s], S=0**

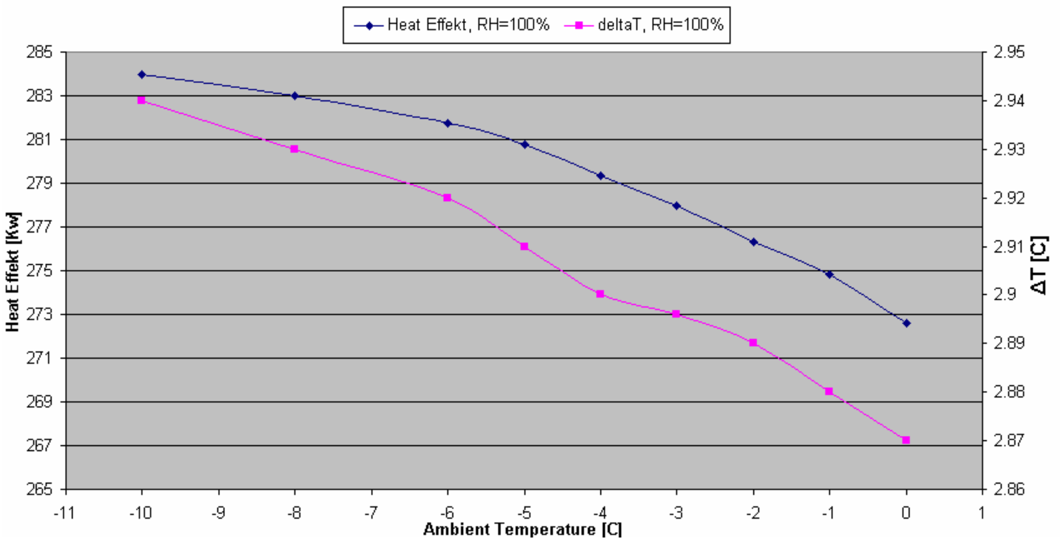

**Figure 10.8** $V_2=80$ **[m/s], S=2**

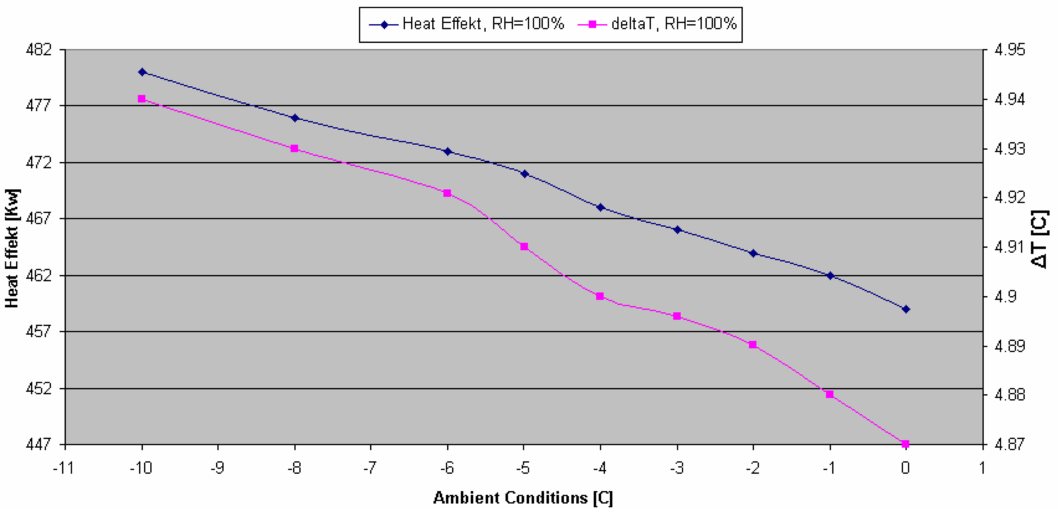

Figure 10.9 $V_2$=80 [m/s], S=4

## *II.* $V_2$= 130 [m/s]

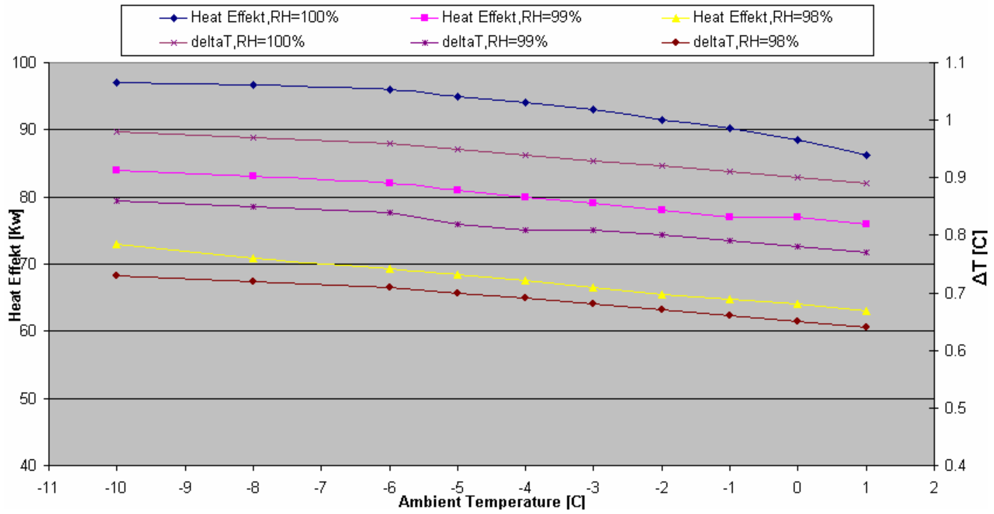

Figure 10.10 $V_2$=130 [m/s], S=0

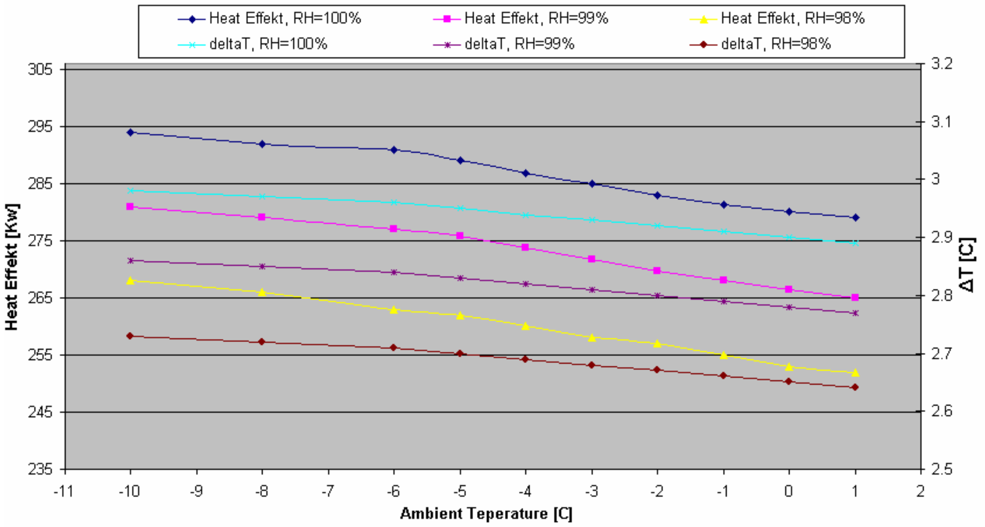

Figure 10.11 $V_2$=130 [m/s], S=2

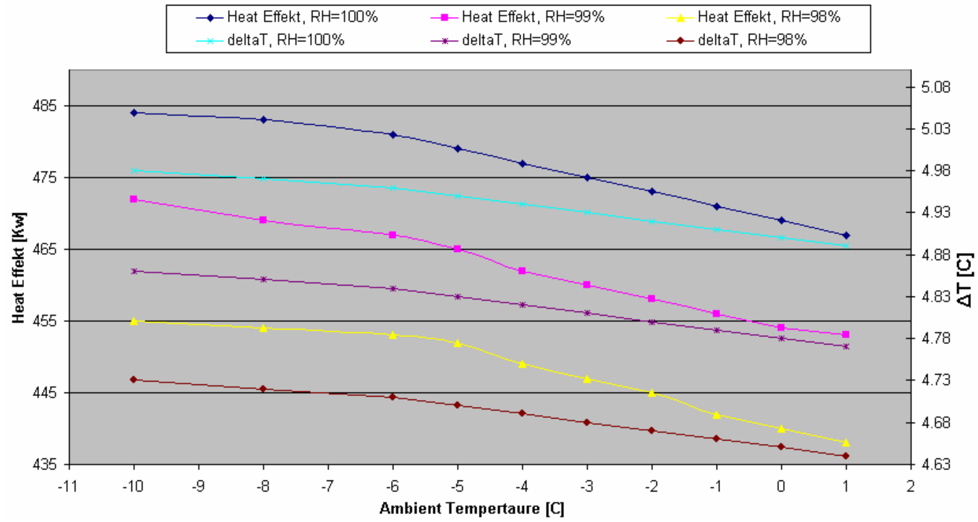

**Figure 10.12** $V_2$=130 [m/s], S=4

## *III.* $V_2$= 150 [m/s]

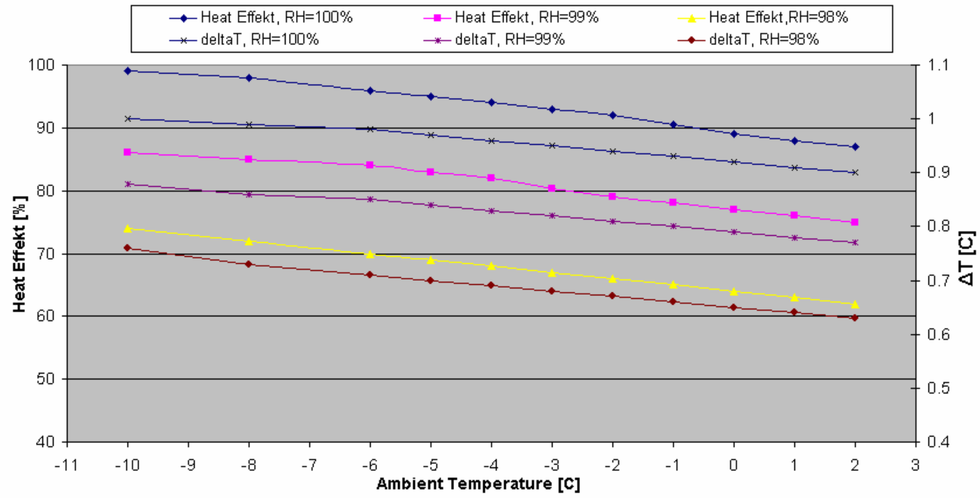

**Figure 10.13** $V_2$=150 [m/s], S=0

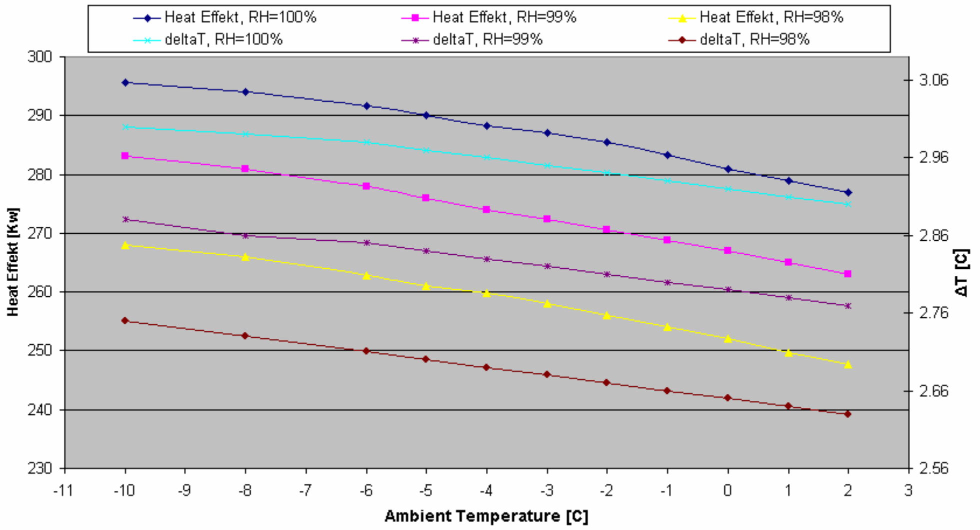

**Figure 10.14** $V_2$=150 [m/s], S=2

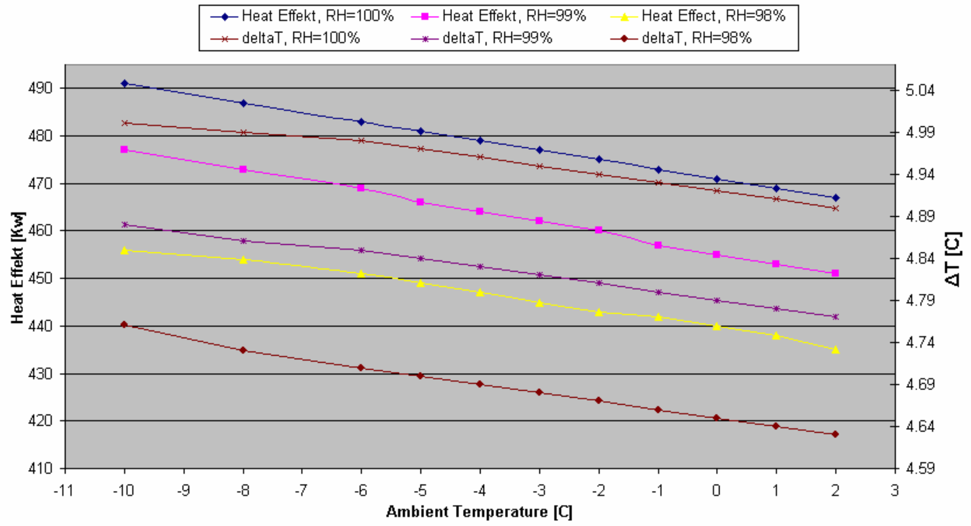

Figure 10.14 $V_2$=150 [m/s], S=4

*IV.* $V_2$= 180

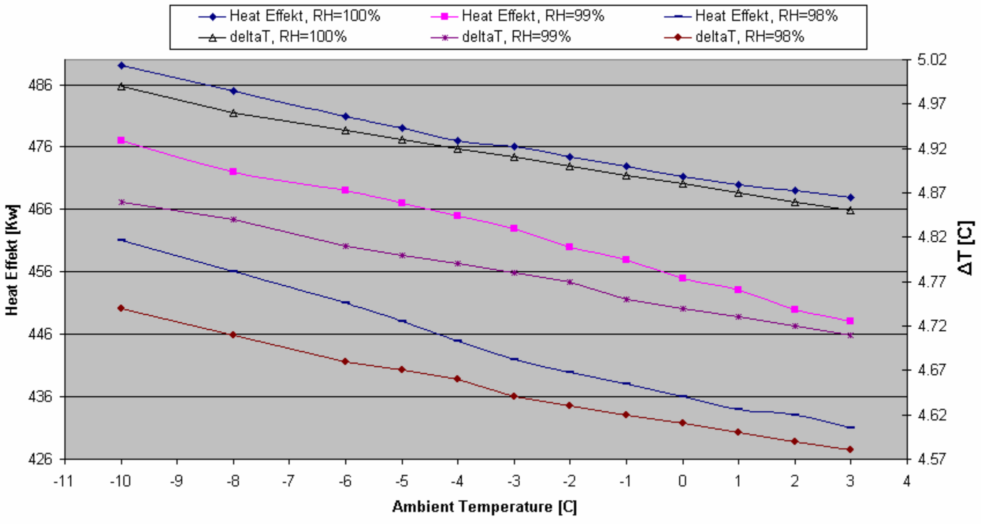

Figure 10.15 $V_2$=180 [m/s], S=0

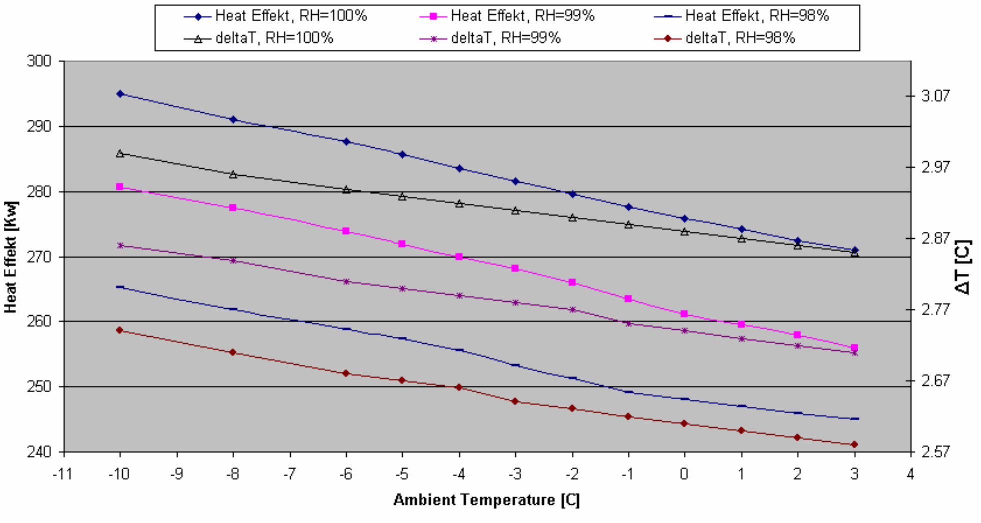

Figure 10.16 $V_2$=180 [m/s], S=2

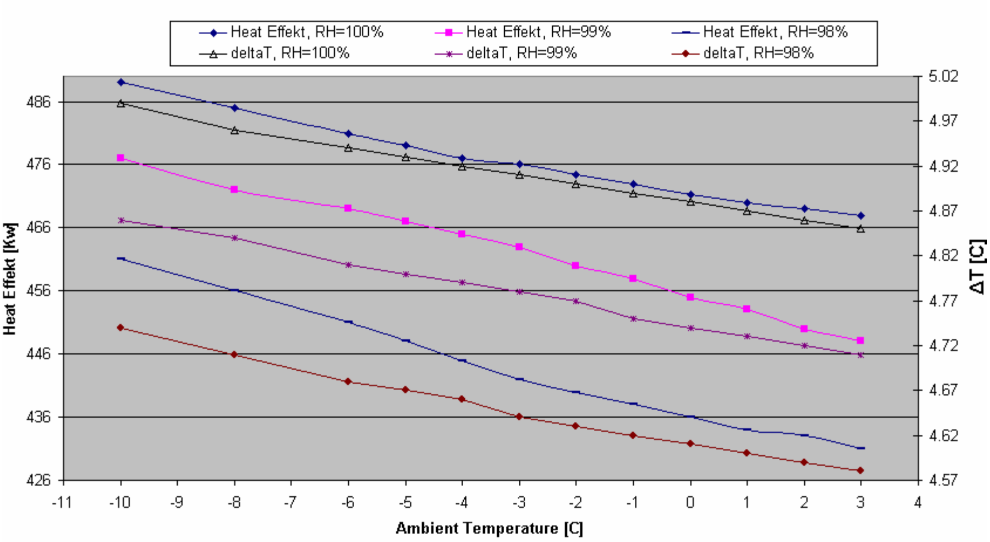

Figure 10.17 $V_2$=180 [m/s], S=4

## *V.* $V_2$= 200 [m/s]

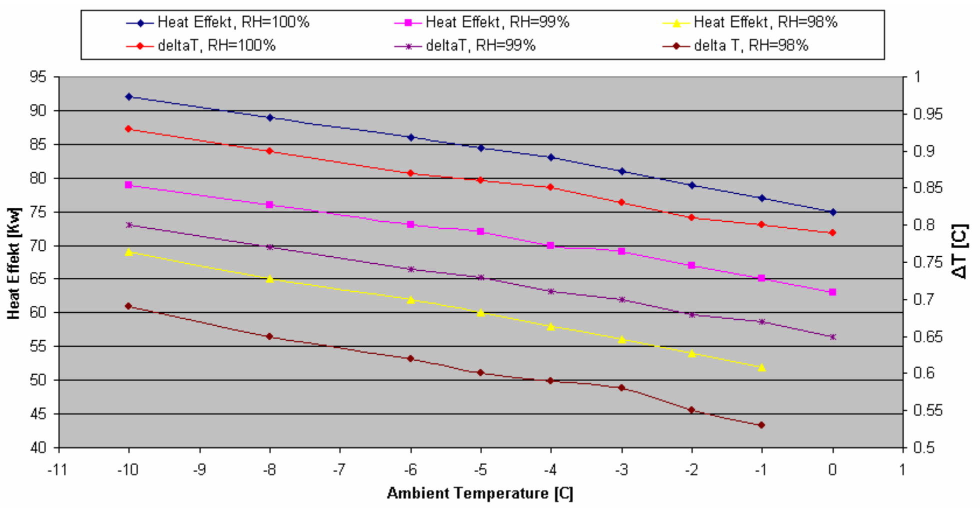

Figure 10.17 $V_2$=200 [m/s], S=0

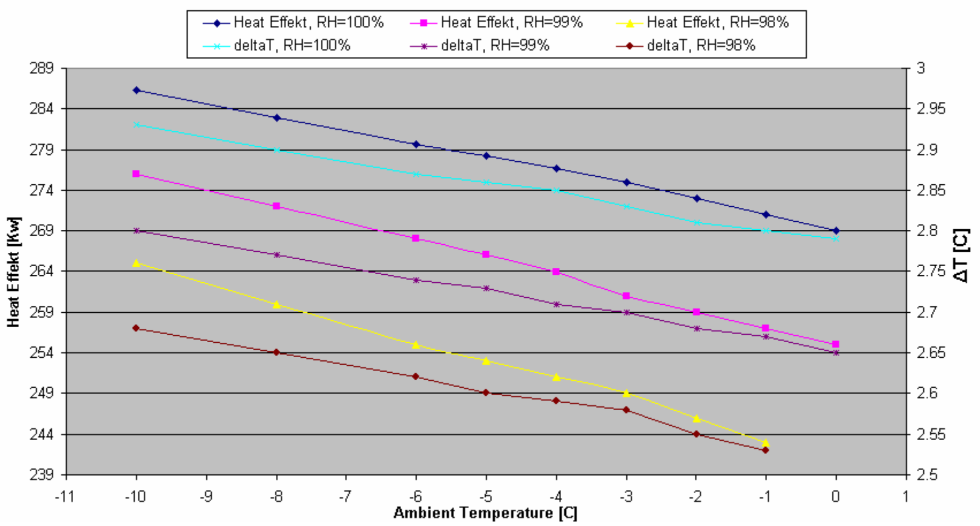

Figure 10.18 $V_2$=200 [m/s], S=2

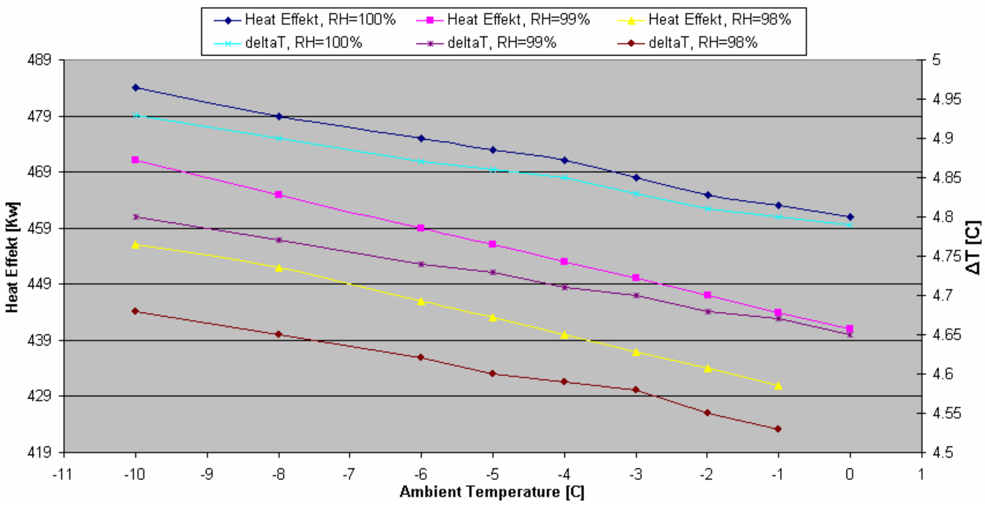

Figure 10.19 $V_2$=200 [m/s], S=4

## 10.2.1.2 Conclusion

From the (Fig. 10.4 to 10.19) various important results can be concluded.

1. The heat power which is required to avoid that ice forms on the surface of the inlet system increases with increasing velocity to a maximal value and then decreases again. This agrees together with the previous conclusion that with very high air velocities the hazard of icing doesn’t exist any more. The highest heat requirement coincides with air velocity 150 [m/s] which is also the critical velocity for icing conditions. By increasing the velocity further more, the heat power decreases.
2. By increasing the ambient temperature the heat power at a constant relative humidity decreases. We can observe that the decreasing of the heat power is slight. This can be explained by the fact that with increased the ambient air temperature, the surface temperature and the dew point temperature increase at the same time. Thus the ΔT which is the difference between dew point temperature and surface temperature experiences a small change. Consequently, the heat power decreases slightly with increasing ambient air temperature.
3. The relative humidity has a great affect on the heat power. It can be noticed from the figures that with reduced the relative humidity the heat power decreases notably at a constant ambient air temperature.
4. The design point for the anti-icing system is the point where the heat power is the greatest. The ambient conditions for this point will be the worst case under operating the gas turbine at icing conditions. This point coincides where the velocity of the air 150 [m/s] and the ambient air temperature is -10 $C^o$ with 100 % relative humidity. The heat power will be therefore 491 [kW].

### *10.2.2 SGT-800*

The Siemens SGT-800 Industrial gas turbine (formerly known as the GTX100) combines reliable, industrial design with high efficiency and low emission levels. The SGT-800 allows implementing low life-cycle cost solution for combined heat and power production. It designed for heavy-duty operation. SGT-800 operates in both open cycle as well as combined cycle installations. The SGT-800 is a single shaft machine with 15 compressor stages of which the first three stationary stages have variable geometry (Fig. 10.20). To ensure durability and long life, the first stage blade is made of single-crystal materials. Table (10.2) shows SGT-800 characteristics. The anti-icing system which is used in this SGT-800 that operates in combined power plant is a water heat exchanger. This system uses warm water from the combined plant as a heat source.

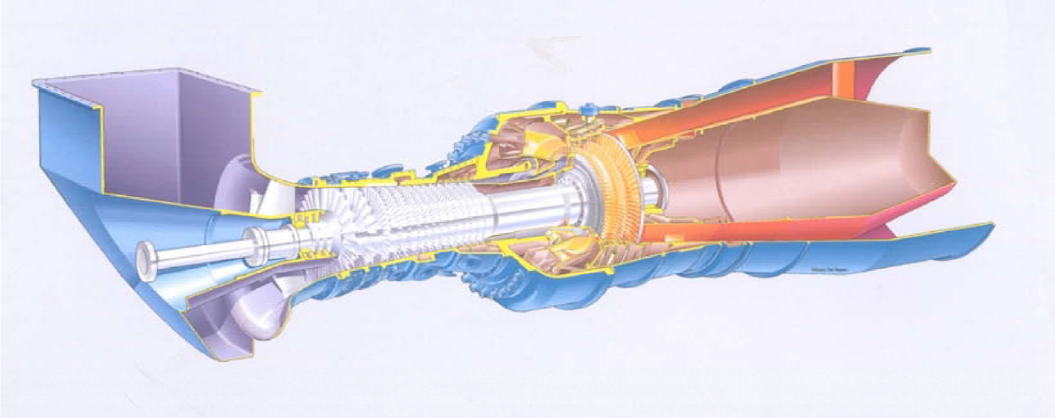

**Figure 10.20 SGT-800 [85]**

| | Power Generation |
|---|---|
| **Output [MW]** | 45 |
| **Electrical efficiency [%]** | 37 |
| **Compressor pressure ratio** | 19,3: 1 |
| **Power turbine speed [rpm]** | 6608 |

**Table 10.2 SGT-800 characteristics [85]**

For same ambient conditions as for gas turbine SGT-700, the calculation will be done again to decide the heat power to avoid ice formation on the surface of the inlet system of the SGT-800. The calculation will handle only the heat power thus the dimensions of the heat exchanger will not be taken in account in this study. The heat effect is given in the following equation:

$$Q_{H.E} = m_{air} \cdot Cp \cdot \Delta t \qquad [kW] \quad (10.9)$$

$Q_{H.E}$ : The heat power that needs to avoid ice formation. [kW]
$m_{air}$ : The air mass flow in the intake system [kg/s]

Cp: Specific heat capacity of the air [kJ/kg.K]
$\Delta t$ : Temperature different to keep the icing surface free from ice [C°]

The different between the dew point temperature and the surface temperature in the inlet system is equal to the different between the temperature in the compressor inlet after heating and the ambient air temperature. Thus the inlet compressor temperature that results from warming up the cold ambient air when it passes over the heat exchanger can be calculated as following:

$$\Delta T = T_{\text{dew point}} - T_{\text{surface}} \qquad [C^{o}] \quad (10.10)$$

$\Delta T$ : The different between the dew point and the surface temperature [C°]
$T_{\text{dew point}}$: Dew point temperature of the air in the inlet system [C°]
$T_{\text{surface}}$: Icing Surface temperature [C°]

$$\Delta t = t_2 - t_o \rightarrow t_2 = \Delta t + t_o \qquad [C^{o}] \quad (10.11)$$

$\Delta t$: Temperature different to keep the icing surface free from ice [C°]
$t_2$: Inlet air temperature to the compressor [C°]
$t_o$: Ambient air temperature [C°]

The new relative humidity which corresponds to the inlet air temperature to the compressor after heating can be calculated by

$$RH = \frac{\omega . P_{o1}}{(0{,}6236 + \omega) . P_{\upsilon @ t2}} . 100 \qquad [\%] \; (10.12)$$

RH : Relative humidity after warming up the ambient air [%]
$P_{o1}$ : Ambient air pressure [bar]
$\omega$ : Absolute humidity of the air which is constant before and after heating the air [kg/kg]
$P_{\upsilon @ t2}$ : Partial pressure of the water at temperature $t_2$ [bar]

By replacing air temperature and relative humidity of the air after heating in the Siemens program GT- Performance, we can get the air composition and air mass flow after warming up the cold ambient air in front of the intake system.
($t_2$, RH) in the GT- Performance → $m_{air}$ , Air Composition. (10.13)

It will be possible now to obtain specific heat capacity of the inlet air to the intake system after heating

Cp= f (t2, Air Composition) [kJ/kg.K] (10.14)
By replacing these values in the equation (10.9) we get the requirement heat effect to keep the surface of the inlet system clear from ice. The calculations have been made in the same way as it has been made for SGT-800.In other word they have been made for various air velocities and with safety factors (0, 2 and 4). The results are demonstrated as following

### 10.2.2.1 Heat power

*I.* $V_2$= 50 [m/s]

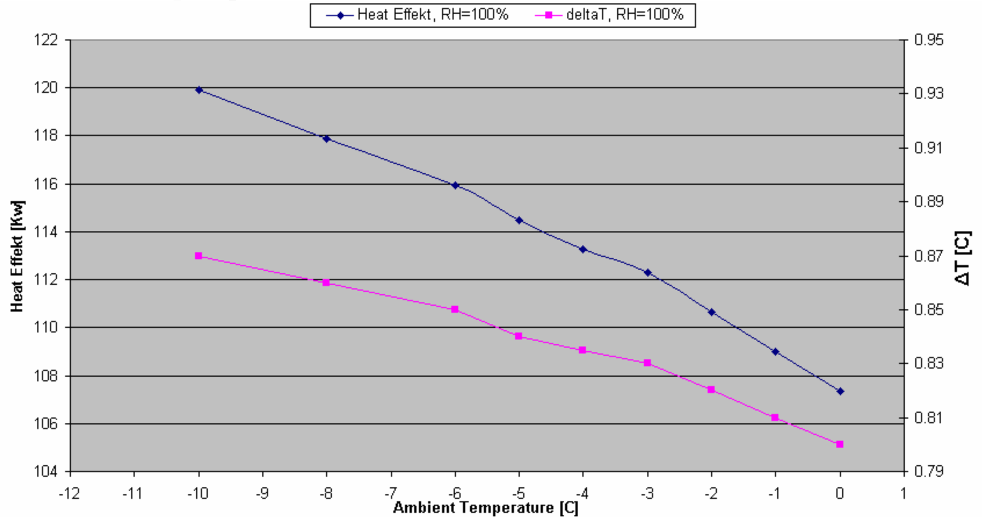

**Figure 10.21** $V_2$=50 [m/s], S=0

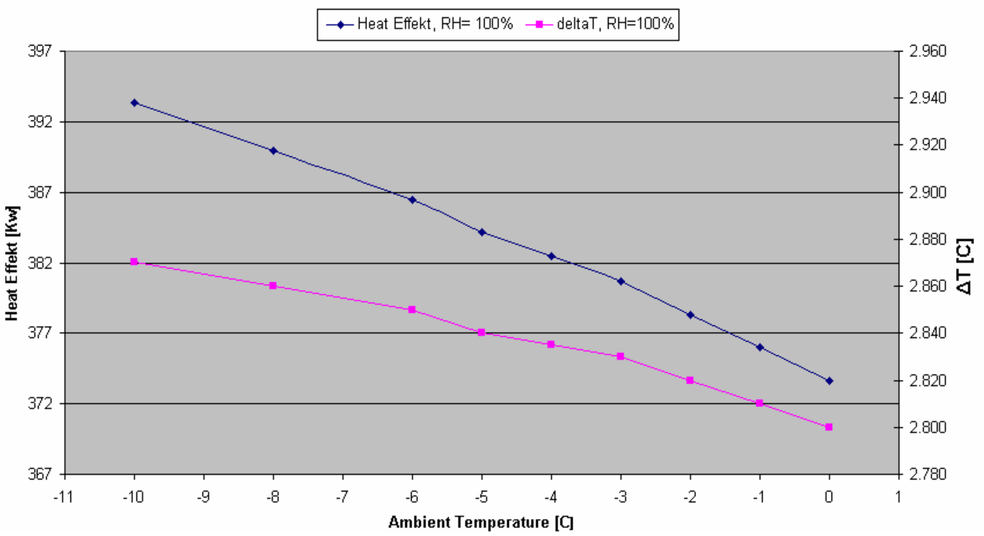

**Figure 10.22** $V_2$=50 [m/s], S=2

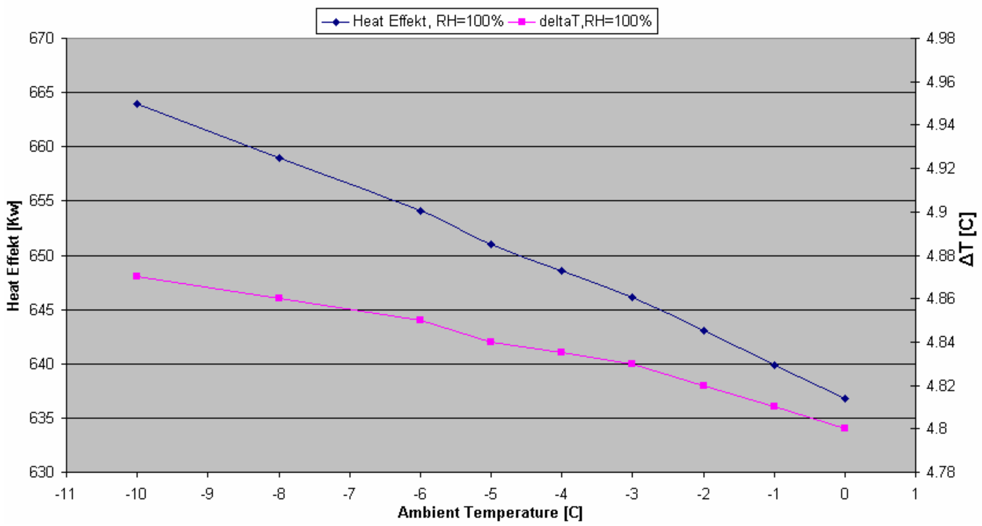

**Figure 10.23** $V_2$=50 [m/s], S=4

## *II.* $V_2$= 130 [m/s]

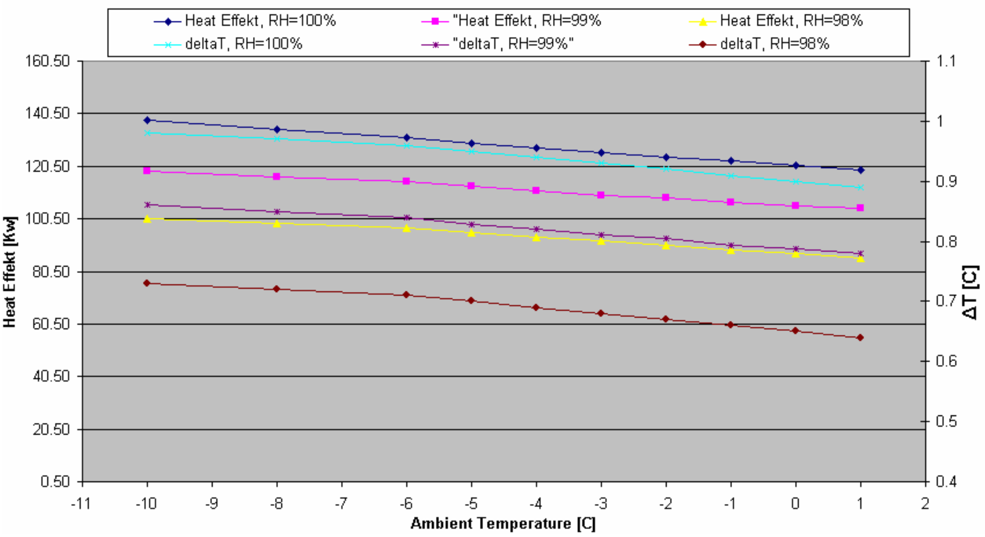

**Figure 10.24** $V_2$=130 [m/s], S=0

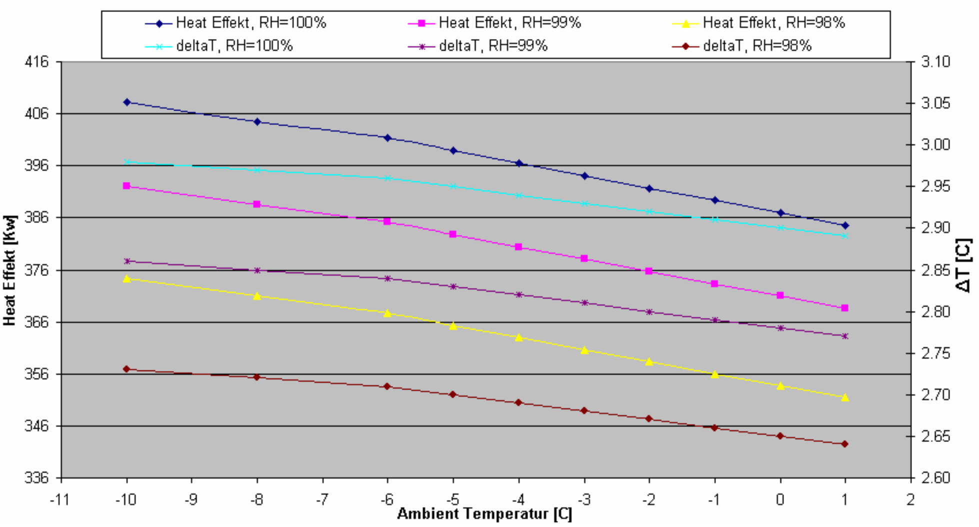

**Figure 10.25** $V_2$=130 [m/s], S=2

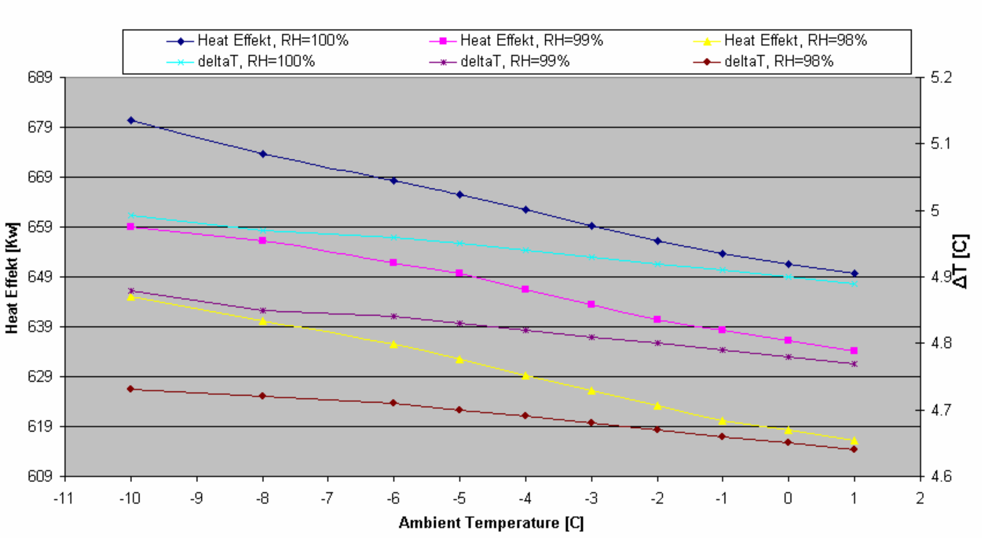

**Figure 10.26** $V_2$=130 [m/s], S=4

*III.* $V_2$= 150 [m/s]

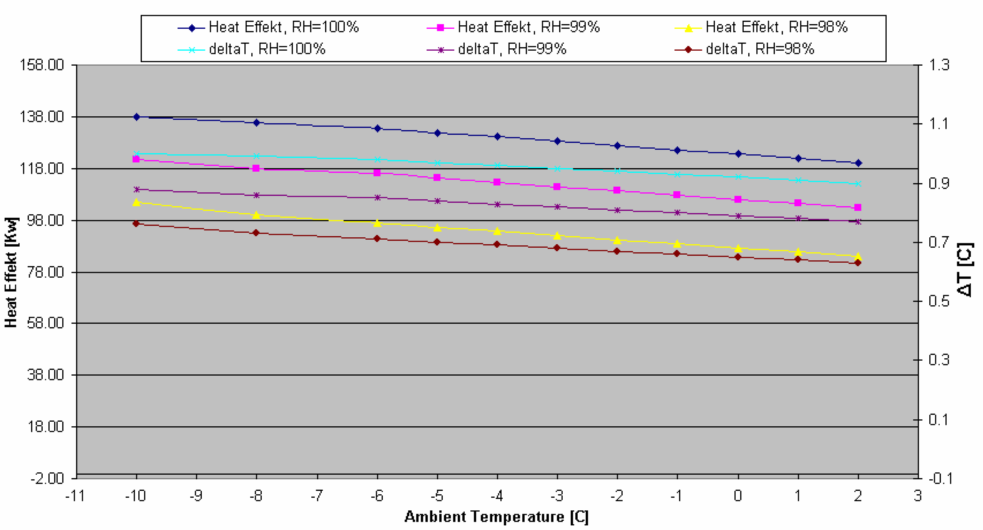

**Figure 10.27 $V_2$=150 [m/s], S=0**

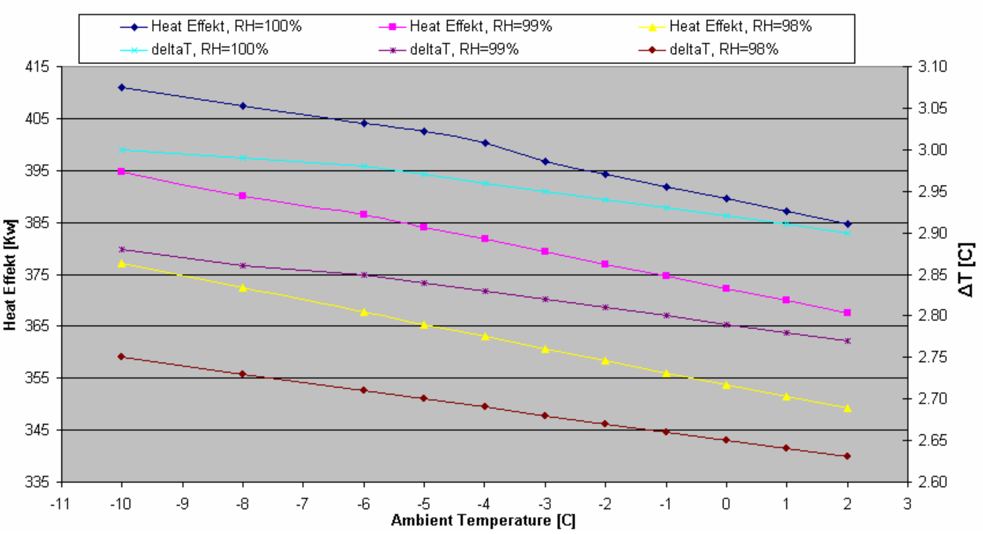

**Figure 10.28 $V_2$=150 [m/s], S=2**

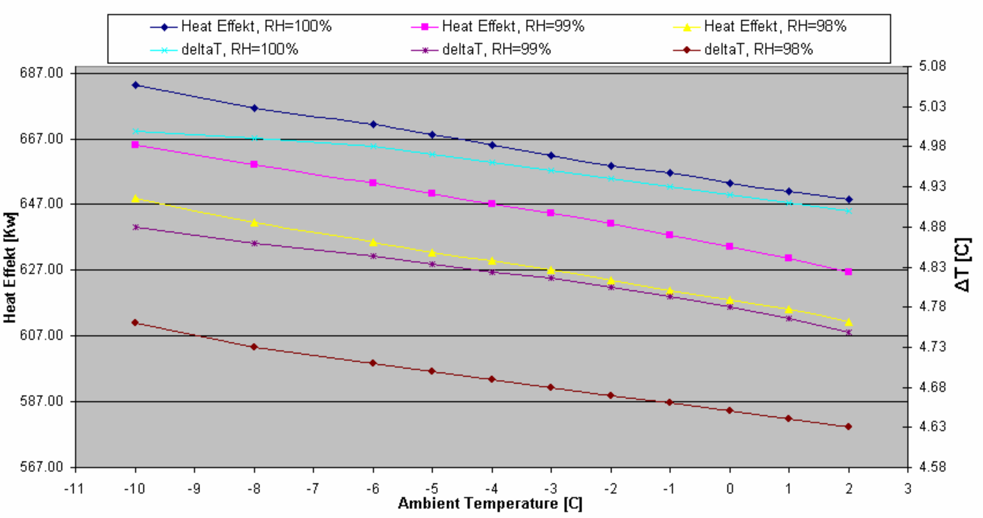

**Figure 10.29 $V_2$=150 [m/s], S=4**

## *IV.* $V_2$= 180 [m/s]

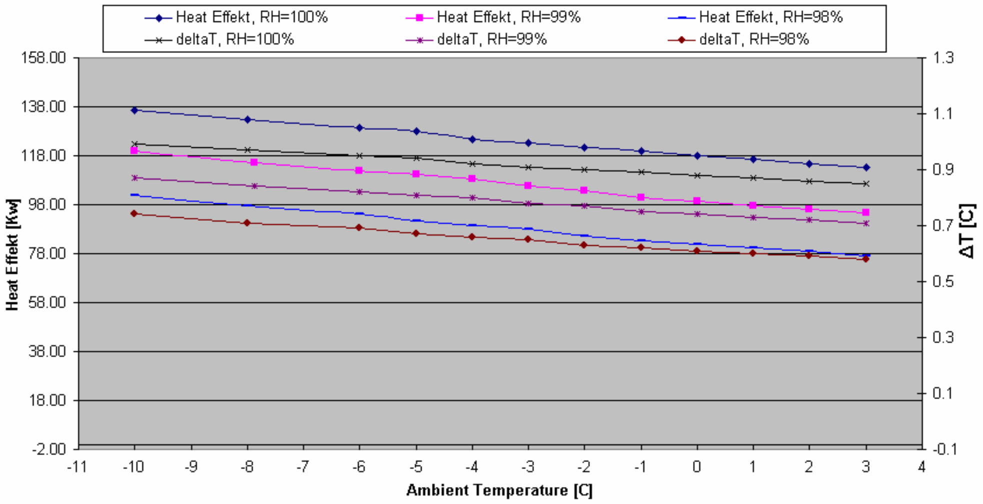

**Figure 10.30 $V_2$=180 [m/s], S=0**

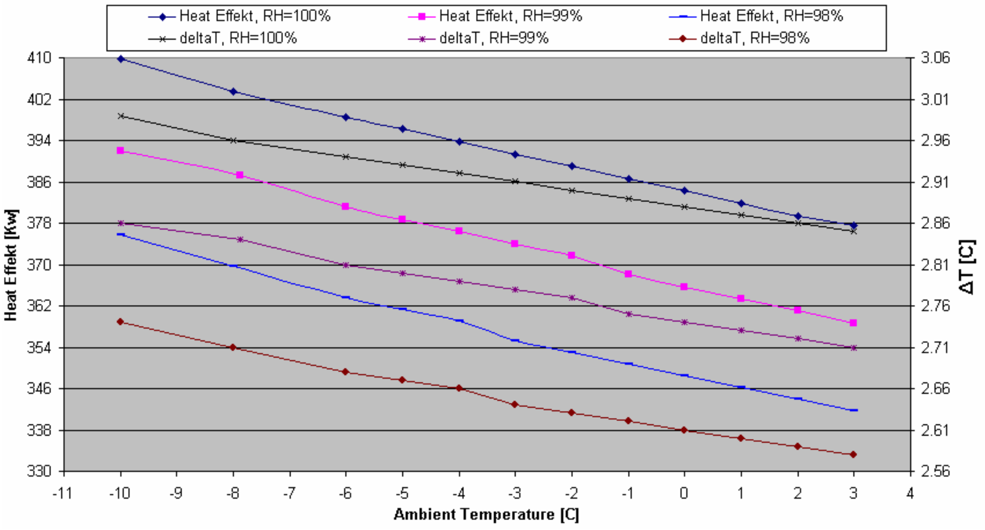

**Figure 10.31 $V_2$=180 [m/s], S=2**

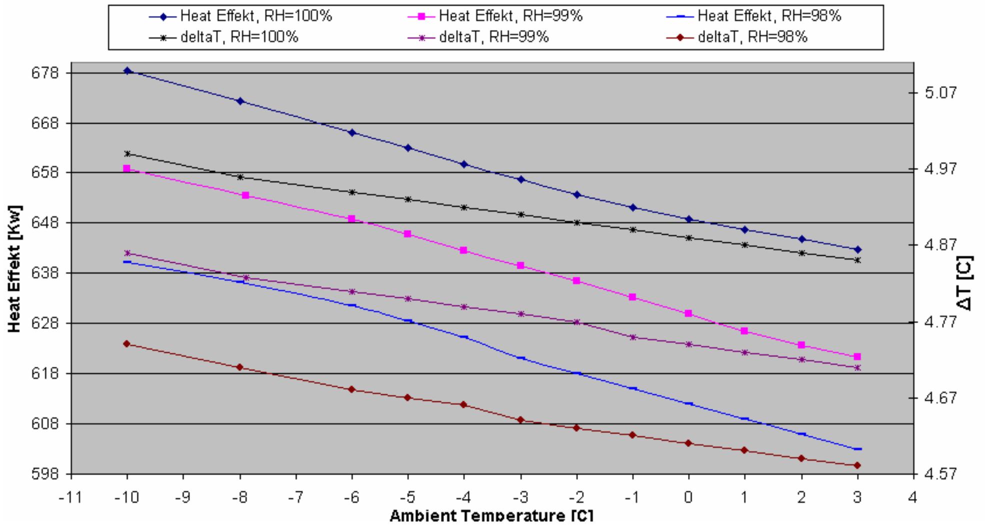

**Figure 10.32 $V_2$=180 [m/s], S=4**

### *V.* $V_2$= 200 [m/s]

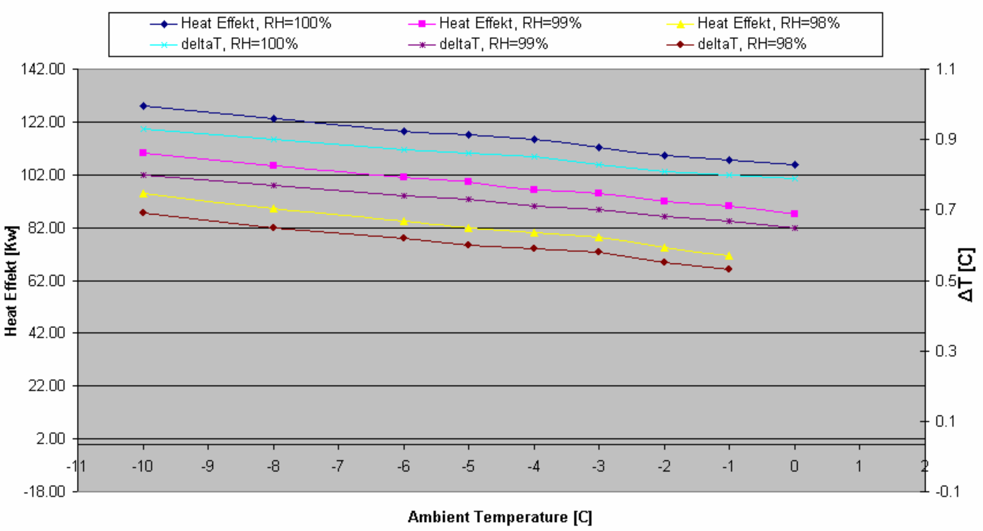

**Figure 10.33** $V_2$=200 [m/s], S=0

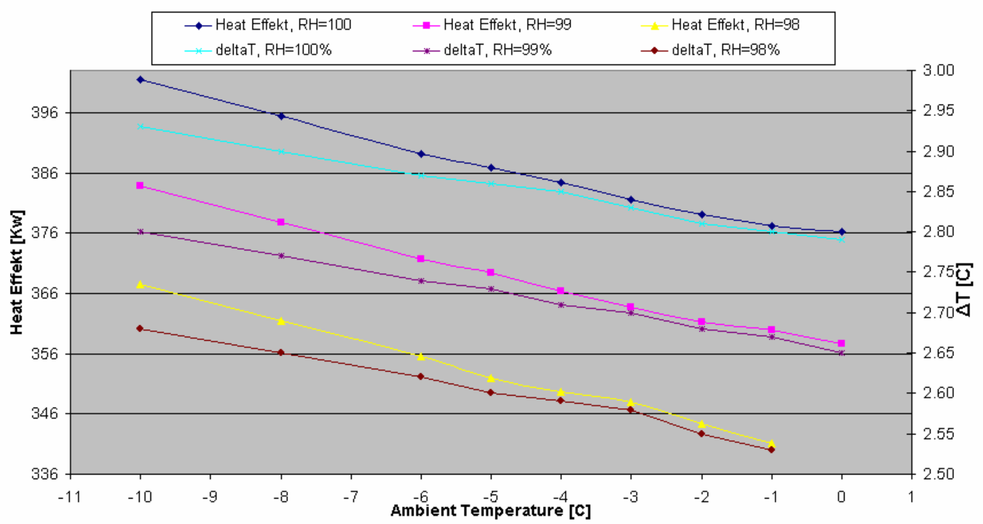

**Figure 10.34** $V_2$=200 [m/s], S=2

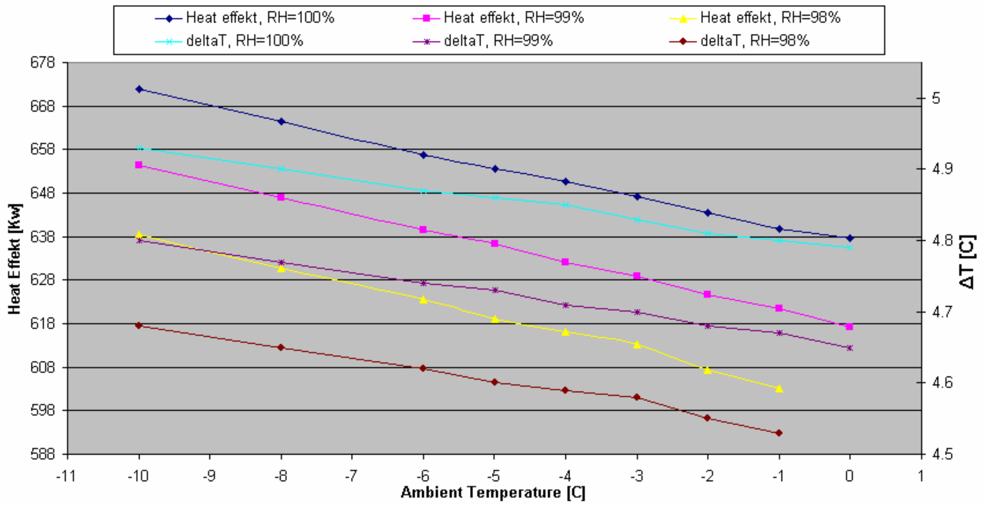

**Figure 10.35** $V_2$=200 [m/s], S=4

#### 10.2.2.2 Conclusion

From (Fig. 10.21 to 10.35) we can conclude the same results which have been concluded from the SGT-700. The most important conclusions from SGT-800 results are

1. The maximum heat power coincides with air velocity 150 [m/s] and with ambient conditions -10 $C^o$ and relative humidity 100 %. This agrees with the results for SGT-700.
2. The heat power is lower with using the heat exchanger as an anti-icing system in SGT-800 than it is with using bleed heat compressor as an anti-icing system in SGT-700. Heat power is 683,4 [kW] in SGT-800 while its 491 [kW] in SGT-700

## 10.3 Anti-icing system effects on gas turbine performance

The anti-icing system has an influence on the gas turbine performance. The power output and the thermal efficiency of the gas turbine decrease through using a part of the heat in the system to warm up the incoming air to the intake system. The bleeds heating system has greater influence on the gas turbine performance than heat exchanger has. The following tables show the output power and thermal efficiency of the SGT-700 and SGT-800 before and after the anti-icing system in the intake system at relative humidity 100%. This is because of the maximal heat requirement to avoid the ice formation in the inlet system coincides with relative humidity 100%. The table (10.3) shows the bleeds heating anti icing system effect on the power output and thermal efficiency for SGT-700. The table (10.4) presents the effect of both bleeds heating system anti icing system and water heat exchanger system on the power output and thermal efficiency of the SGT-800.

### *10.3.1 SGT-700*

| **Anti-icing system** | **$T_{ambient,Air}$** | **$RH_{ambient,Air}$** | **GT-power (Electric)** | **GT Thermal Efficiency (Electric)** |
|---|---|---|---|---|
| | **[C]** | **[%]** | **[kW]** | **[%]** |
| Non anti-icing system | -10,00 | 100,00 | 33614 | 36,95 |
| Bleed | -5,00 | 67,94 | 32485 | 36,55 |
| Heat Exchanger | -5,00 | 67,94 | 33079 | 36,98 |
| Δ Bleed | -5,00 | 32,06 | 1129 | 0,40 |
| Δ Heat Exchanger | -5,00 | 32,06 | 534 | -0,02 |
| Non anti-icing system | -8,00 | 100,00 | 33403 | 36,96 |
| Bleed | -3,01 | 68,48 | 32193 | 36,52 |
| Heat Exchanger | -3,01 | 68,48 | 32875 | 36,98 |
| Δ Bleed | -4,99 | 31,52 | 1210 | 0,44 |
| Δ Heat Exchanger | -4,99 | 31,52 | 528 | -0,02 |
| Non anti-icing system | -6,00 | 100,00 | 33195 | 36,97 |
| Bleed | -1,02 | 68,96 | 31807 | 36,46 |
| Heat Exchanger | -1,02 | 68,96 | 32621 | 36,97 |
| Δ Bleed | -4,98 | 31,04 | 1389 | 0,51 |
| Δ Heat Exchanger | -4,98 | 31,04 | 575 | 0,00 |
| Non anti-icing system | -5,00 | 100,00 | 33093 | 36,97 |
| Bleed | -0,03 | 69,22 | 31623 | 36,43 |
| Heat Exchanger | -0,03 | 69,22 | 32427 | 36,94 |
| Δ Bleed | -4,97 | 30,78 | 1470 | 0,54 |
| Δ Heat Exchanger | -4,97 | 30,78 | 666 | 0,03 |
| Non anti-icing system | -4,00 | 100,00 | 32991 | 36,97 |
| Bleed | 0,96 | 69,43 | 31433 | 36,39 |
| Heat Exchanger | 0,96 | 69,43 | 32237 | 36,91 |
| Δ Bleed | -4,96 | 30,57 | 1558 | 0,58 |
| Δ Heat Exchanger | -4,96 | 30,57 | 754 | 0,06 |
| Non anti-icing system | -3,00 | 100,00 | 32890 | 36,97 |
| Bleed | 1,95 | 69,69 | 31236 | 36,35 |
| Heat Exchanger | 1,95 | 69,69 | 32047 | 36,87 |
| Δ Bleed | -4,95 | 30,31 | 1654 | 0,62 |
| Δ Heat Exchanger | -4,95 | 30,31 | 842 | 0,10 |

| **Anti-icing system** | **$T_{ambient,Air}$** | **$RH_{ambient,Air}$** | **GT-power (Electric)** | **GT Thermal Efficiency (Electric)** |
|---|---|---|---|---|
| | **[C]** | **[%]** | **[kW]** | **[%]** |
| Non anti-icing system | -2,00 | 100,00 | 32790 | 36,97 |
| Bleed | 2,94 | 69,90 | 31040 | 36,30 |
| Heat Exchanger | 2,94 | 69,90 | 31858 | 36,84 |
| Δ Bleed | -4,94 | 30,10 | 1750 | 0,67 |
| Δ Heat Exchanger | -4,94 | 30,10 | 931 | 0,13 |
| Non anti-icing system | -1,00 | 100,00 | 32641 | 36,96 |
| Bleed | 3,93 | 70,15 | 30853 | 36,26 |
| Heat Exchanger | 3,93 | 70,15 | 31673 | 36,81 |
| Δ Bleed | -4,93 | 29,85 | 1788 | 0,70 |
| Δ Heat Exchanger | -4,93 | 29,85 | 968 | 0,15 |
| Non anti-icing system | 0,00 | 100,00 | 32448 | 36,93 |
| Bleed | 4,92 | 70,40 | 30662 | 36,22 |
| Heat Exchanger | 4,92 | 70,40 | 31488 | 36,77 |
| Δ Bleed | -4,92 | 29,60 | 1786 | 0,71 |
| Δ Heat Exchanger | -4,92 | 29,60 | 960 | 0,15 |
| Non anti-icing system | 1,00 | 100,00 | 32257 | 36,89 |
| Bleed | 5,91 | 70,65 | 30473 | 36,17 |
| Heat Exchanger | 5,91 | 70,65 | 31296 | 36,73 |
| Δ Bleed | -4,91 | 29,35 | 1783 | 0,72 |
| Δ Heat Exchanger | -4,91 | 29,35 | 960 | 0,16 |
| Non anti-icing system | 2,00 | 100,00 | 32068 | 36,86 |
| Bleed | 6,90 | 70,85 | 30289 | 36,13 |
| Heat Exchanger | 6,90 | 70,85 | 31105 | 36,69 |
| Δ Bleed | -4,90 | 29,15 | 1779 | 0,73 |
| Δ Heat Exchanger | -4,90 | 29,15 | 962 | 0,17 |

**Table 10.3 SGT-700 performance**

The first two columns show the change in ambient conditions before and after introducing the anti-icing system in the intake system of the gas turbine. The changes in the ambient conditions in both anti-icing systems are same because of it needs the same amount of heat to avoid ice formation. But the loss in the power output and thermal efficiency is greater with bleed anti-icing system than it is with using the water heat exchanger as an anti-icing system. Extracting hot air from the compressor has a greater influence on the gas turbine performance. As a consequence it's more economical to apply heat exchanger as anti-icing system in SGT-700 when the gas turbine applied in combined cycles.

### *10.3.2 SGT-800*

| **Anti-icing system** | $T_{ambient,Air}$ | $RH_{ambient,Air}$ | **GT-power (Electric)** | **GT Thermal Efficiency (Electric)** |
|---|---|---|---|---|
| | **[C]** | **[%]** | **[kW]** | **[%]** |
| Non anti-icing system | -10,00 | 100,00 | 49649 | 37,24 |
| Bleed | -5,00 | 67,94 | 48619 | 37,16 |
| Δ Bleed | -5,00 | 32,06 | 1029 | 0,08 |
| Non anti-icing system | -8,00 | 100,00 | 49251 | 37,21 |
| Bleed | -3,01 | 68,48 | 48220 | 37,13 |
| Δ Bleed | -4,99 | 31,52 | 1030 | 0,08 |
| Non anti-icing system | -6,00 | 100,00 | 48854 | 37,18 |
| Bleed | -1,02 | 68,96 | 47830 | 37,10 |
| Δ Bleed | -4,98 | 31,04 | 1024 | 0,08 |
| Non anti-icing system | -5,00 | 100,00 | 48657 | 37,16 |
| Bleed | -0,03 | 69,22 | 47660 | 37,09 |
| Δ Bleed | -4,97 | 30,78 | 998 | 0,07 |
| Non anti-icing system | -4,00 | 100,00 | 48459 | 37,15 |
| Bleed | 0,96 | 69,43 | 47474 | 37,09 |
| Δ Bleed | -4,96 | 30,57 | 984 | 0,06 |
| Non anti-icing system | -3,00 | 100,00 | 48261 | 37,13 |
| Bleed | 1,95 | 69,69 | 47288 | 37,08 |
| Δ Bleed | -4,95 | 30,31 | 974 | 0,05 |
| Non anti-icing system | -2,00 | 100,00 | 48065 | 37,11 |
| Bleed | 2,94 | 69,90 | 47100 | 37,07 |
| Δ Bleed | -4,94 | 30,10 | 965 | 0,04 |
| Non anti-icing system | -1,00 | 100,00 | 47878 | 37,10 |
| Bleed | 3,93 | 70,15 | 46908 | 37,06 |
| Δ Bleed | -4,93 | 29,85 | 971 | 0,04 |
| Non anti-icing system | 0,00 | 100,00 | 47710 | 37,10 |
| Bleed | 4,92 | 70,40 | 46715 | 37,05 |
| Δ Bleed | -4,92 | 29,60 | 995 | 0,05 |
| Non anti-icing system | 1,00 | 100,00 | 47525 | 37,09 |
| Bleed | 5,91 | 70,65 | 46523 | 37,04 |
| Δ Bleed | -4,91 | 29,35 | 1003 | 0,06 |
| Non anti-icing system | 2,00 | 100,00 | 47340 | 37,08 |
| Bleed | 6,90 | 70,85 | 46329 | 37,02 |
| Δ Bleed | -4,90 | 29,15 | 1011 | 0,06 |

**Table 10.4 SGT-800 performance**

The first two columns in table (10.4) present the changes in the ambient conditions before and after introducing the warm air, extracted from the compressor in front of the intake system. Both the ambient air temperature and the relative humidity decrease with warming up the incoming air to the gas turbine. The influence of the compressor bleeds heating has great effects on the gas turbine performance.

# 11. Sensors

The anti-icing protection systems are generally controlled by sensors [36]. These sensors minimize the heat power to keep all parts of the inlet system free of ice. This leads to a minimum necessary amount of heat extracted from the anti-icing system. The sensors used in stationary gas turbine installations can be divided into two groups depending on how they predict ice formation; I*ce Sensors* and *Icing Conditions Sensors* [36].

## 11.1 Ice sensors

Ice sensors detect both condensate ice and precipitate ice. The ice sensor is a sensing element or a probe that is exposed to the air stream through the inlet system of the gas turbine. When small amounts of ice build up on the sensor leading side, the sensor frequency will change. A signal is then given to the anti-icing system to be activated [36]. The advantage with this type of sensor is that the anti-icing system is activated only when an actual icing at the location of the probe takes place. It is obvious that judicious positioning of the probe is very important. It's not easy to find the exact place where ice forms in the inlet system. Thus more than one probe may be required to ensure that ice will be detected. In order to cover condensate icing, the probe has to be placed inside the gas turbine, near the protected components. There are many kinds of ice sensors in services in both ground and aircraft gas turbines. In this thesis I will present three ice sensors; Rosemount RMT 872 DE and EW 140 from Vibro-meter that both have been applied in stationary gas turbines. Last I will present the Ice Meister Model 9732-OEM that has been applied in aircraft gas turbines.

### *11.1.1 Rosemount RMT 872 DE*

#### 11.1.1.1 Concept

Rosemount RMT 872 DE is an instrument that was developed by Rosemount Engineering, Minnesota for detection of supercooled liquid water content and the onset of airframe icing [73]. Rosemount ice sensor is a rod exposed to air stream that is excited to a particular frequency (Fig. 11.1) [36]. Rosemount detectors measure the amount of ice mass accumulation on metal cylinders using a property known as magnetostriction. The sensing cylinder is driven at a natural frequency of 40 kHz. When small amounts of ice build up on its leading side, the frequency of the vibration decreases [73]. A phase-locked loop converts this frequency change to a proportional voltage from which the ice mass can be calculated. Once a pre-set amount of mass has been accumulated, two actions will take place. A signal will be given to activate the anti-icing system and the rod will be heated and melt the ice preparing for a new cycle [36]

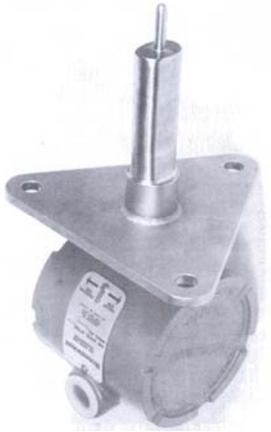

Figure 11.1 Rosemount RMT 872 DE [36]

### 11.1.2 EW 140

#### 11.1.2.1 Concept

The ice detection system has been designed by Vibro- Meter Company. The first time it was used was in 1978 on an aircraft to detect ice, and it showed successful results. The ice detection system consists of the ice sensor EW 140 and DIC 413 de-icing conditioner [74].

*EW 140 ice sensor* is designed for use in turbomachinery applications and senses ice formation on its surface (Fig. 11.2). It can operate in environments where the air ambient temperature is low down to –55 [C$^o$] [74].

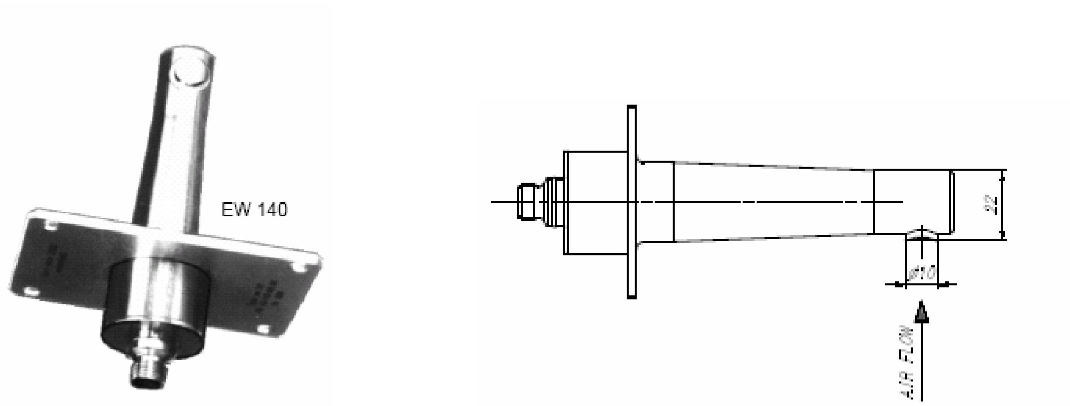

Figure 11.2 EW 140 [74]

The principle of operation is that the natural frequency of a solid body changes depending on mass or stiffness. EW 140 sensor has a vibrating diaphragm that is forced into oscillation by a piezoelectric material at ultrasonic frequency. Ice accretion on the diaphragm increases the average stiffness of the diaphragm, causing the natural frequency of the system to increase according to ice thickness [74]. The variation in frequency is processed to give a signal proportional to the ice thickness. Water or liquid containments cause the diaphragm mass to increase which leads to a decrease in the natural frequency, giving a clear discrimination between ice and water (Fig. 11.3) [74].

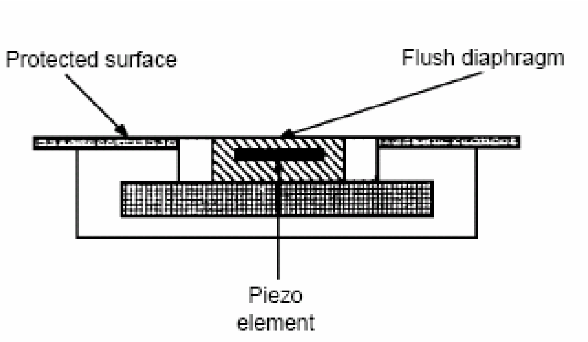

**Figure 11.3 EW construction [74]**

*DIC 413 De-Icing Controller* is designed to match the EW 140 ice sensor and it usually placed 150 m away from the turbine (Fig. 11.4). It reads the current signal from EW 140 ice sensor and converts this signal into an analog voltage. DIC 413 can be used as an actuator for visible or audible alarm systems and/or an automatic controller for activating the de-icing system (Bleed air system) [74]. There are two different signals provided as a standard; an OK signal and an ICE alarm. The OK signal indicates that the system is functioning normally and that no ice is present. The ICE alarm is activated when a pre-selected ice thickness has been attained. At present during installation, one of five different thicknesses of ice may be selected to generate the alarm [30].

**Figure 11.4 DIC 413 De-Icing Controller [74]**

### 11.1.2.2 Calibration and maintenance

There is practically no calibration needed for the sensor because of the design of the membrane that decides the resonance frequency. This remains the same after fabrication, unless the membrane is damaged by an external influence. However, over time, there could be a build up of containments on the sensor as well as on the compressor blades. A suitable washing procedure will return the sensor to its original condition. It's recommended to clean of the sensor under compressor service and washing [30].

### 11.1.2.3 Advantages

1. No moving parts
2. High reliability
3. Discrimination between ice and water or other liquid contaminates
4. Choice of 3 probe lengths

5. Measurement range 0.2 to 2.0 mm
6. Analog output (voltage) indicating ice thickness [74]

This sensor has been in operation on Siemens V94.2 gas turbine at the Eemscentrale of EPON in the north of Holland 1991-1994. The sensor has been placed in the air intake of the turbine upstream of the inlet guide vanes in the upper casing about $20^{o}$ above the horizontal (Fig. 11.5) [30]. The system has showed successful results under its operation. General Electric has also applied EW 140 ice sensor on its gas turbine LM2500 and it gave good results during its operation [72].

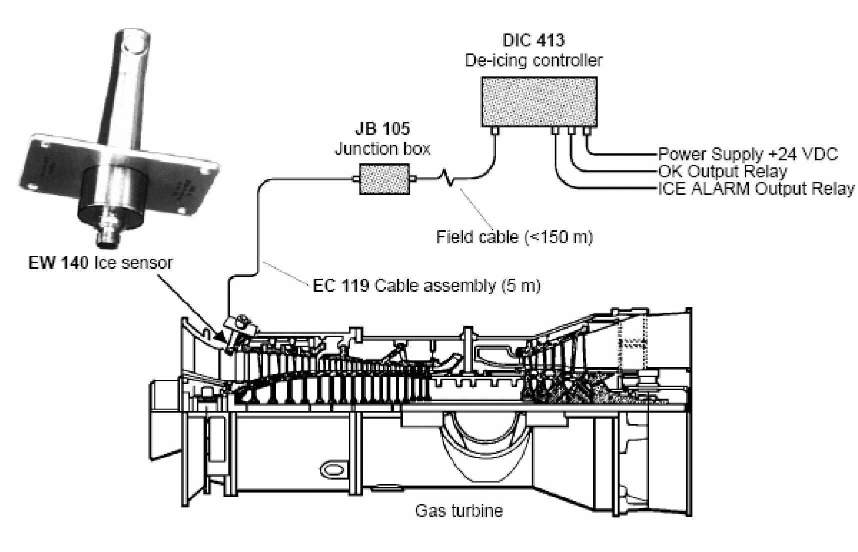

**Figure 11.5 EW position in gas turbine [30]**

## 11.1.3 Ice Meister Model 9732-OEM

### 11.1.3.1 Concept

Ice Meister is applied widely in aircraft applications to detect ice formation on wings and inlet system of the gas turbine struts and IGVs. It's an optical ice-detecting transducer probe that senses the first 0,001 inch (0,025 mm) [71]. It's tiny, lightweight and has a low cost (Fig.11.6).

**Figure 11.6 Ice Meister Model 9732-OEM [71]**

The Ice sensor system alerts the pilot to active the anti-icing system when ice in the gas turbine begins to constitute a hazard to the aircraft. This sensor has a great advantage in discriminating between rime ice and glaze ice (Fig. 11.7). The sensor has been tested by NASA and documented. I didn't find any information saying that this ice sensor has been tested on ground gas turbine applications. But According to their technical data sheet that I have asked for this sensor can be used in anti-icing system applications [71]

**Figure 11.7 Ice discriminating between rime ice and glaze ice [71]**

### 11.1.3.2 Advantages

1. Distinguishing between rime ice and glaze ice.
2. Analog or digital output
3. Detects first 0.001 inch of ice
4. -50 [C°] to +50[C°]
5. No moving parts
6. NASA tested and documented

The following table (11.1) demonstrates the test results, which have been done on the Ice Meister sensor. The report showed the following results without telling where and when the test was performed or even which gas turbine that was examined.

| | Ice type | Temperature [C°] | Response [Sec] |
|---|---|---|---|
| **Test 1** | Rime ice | -20 | <120 |
| **Test 2** | Glaze ice | -3 | <90 |

**Table 11.1 Ice Meister sensor results [71]**

## 11.2 Sensor position in the turbine

By deciding the right position of the ice sensor in the gas turbine, the ice will be detected successfully when present in the gas turbine. This means that it will only be necessary to activate the anti icing system only when the ice sensor gives a signal of presence of ice in the inlet system. This will save a lot of heat and increase the efficiency of the system as well as the gas turbine performance. Thus determination of the icing conditions in the inlet system of the gas turbine is very important in deciding the ice sensor position. As shown in section 10 the condensate icing potential increases with increasing air velocity in the intake system. In my calculations the most likely place for condensate icing coincides with high air velocity 150 [m/s]. Siemens velocity profile calculations shows that this velocity lies somewhere between the IGVs and bellmouth. A number of manufacturers find that the best position is in the bellmouth at the entry to the compressor, for example on the GE LM2500 and Siemens V94.2. Siemens V94.2 has installed its ice sensor EW 140 in the bellmouth with $20^{o}$ from the horizontal [30]. As it seems the most suitable place for the sensor is in the bellmouth or IGVs.

Siemens Turbomachinary AB in Finspång earlier has earlier applied ice sensor in its gas turbines SGT-500 and SGT-800. Hence it didn't detect the ice in the gas turbine as it should though. The ice sensor gave alarm although there was no ice. Siemens relies now on icing conditions sensors temperature and humidity sensors. Because of the uncertainty of the actual conditions when ice will occur, the anti-icing system will operate for a longer period than necessary even though no ice is present. Therefore it's more effective to use ice sensors to detect ice formation in the gas turbine. The ice sensor has to be placed in the bellmouth or in the IGVs where the air velocity is 150 [m/s]. But there are installation and aerodynamics limitations for the ice sensor placing.

## 11.3 Icing conditions sensors

These sensors sense atmospheric conditions that could potentially cause condensate icing in the gas turbine intake system. Condensate icing depends primarily on ambient temperature, relative humidity and the static temperature depression in the inlet, which is a function of the velocity in the inlet. These kinds of sensors are designed to protect only the intake components against condensate icing. The measured quantities are compared with reference values by an electronic logic circuit. If the measured temperature is below that of the selected reference temperature, and if the relative humidity is above the reference one, the anti-icing system will be activated [36].

## 11.4 limitations

There are limitations when installing ice sensors in the bellmouth or IGVs. The ice sensor cannot be installed on the IGVs because it's a turning component and it's very difficult from an installation point of view. Moreover, IGVs is very close to the compressors first rotating stage and by placing an object in the airflow path it will deteriorate the aerodynamic of the flow, which leads to turbulent flow and performance loss. Even if the ice sensor is mounted in the bellmouth, there are limitations for this position as well. The sensor has to be placed at a certain distance from the compressor not to affect the airflow aerodynamics. The sensor length that is exposed to airflow must also be taken into consideration during the installation of the ice sensor. This depends on sensor size, shape and characteristics. Conclusively we can establish that the ice sensor must be mounted between bellmouth and IGVs so that the sensor head projects into the accelerating air stream just ahead of the compressor (Fig. 11.8). Nevertheless, a more detailed study of the sensor position is needed to understand its influence on the gas turbine performance.

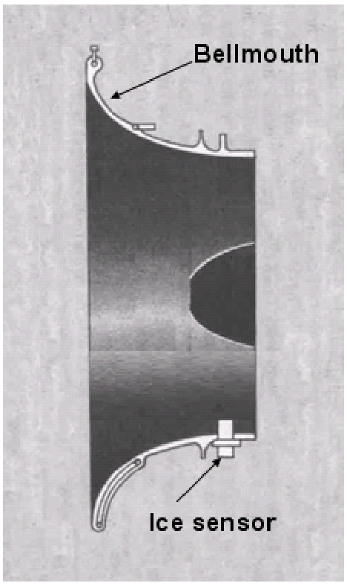

**Figure 11.8 Sensor place in the gas turbine [38]**

# 12. Conclusions

The overall objective of this thesis has been to investigate the icing mechanism in the stationary gas turbines and to figure out different ice types that can form in the gas turbines. It was found that the transparent glaze ice with its high adhesive properties is the kind of ice type that may constitute the most prominent hazard on gas turbines. Glaze ice is hard and if it breaks to small pieces, these pieces can lead to great damage to the compressor (FOD). Therefore glaze can be taken as the design point of anti-icing system.

The condensate ice is the type of ice that results from water vapour condensation from air. The condensate ice hazard increases with increasing air velocity in the inlet system. I found that the highest hazard for glaze ice development does not coincide with at the highest air velocity but at a specific velocity inbetween the lowest and highest velocity. This specific velocity is 150 [m/s]. At high air velocity the temperature depression in the inlet system is great, thus air static temperature becomes very low. With very low air static temperature, below -30 [$C^o$], the water vapour in the air will transfer to ice crystals or/and ice fog. These types of ice don't constitute any hazard on the gas turbine because they just go through the compressor without damaging it.

A very important factor has been taken in the calculations to get the surface temperature. The recovery factor gives the icing surface temperature of the compressor inlet. The surface temperature lies between the static air temperature and total air temperature. I used the theoretical value of the recovery factor which is 0.8 in my calculations.

The ice builds on the icing surface in the inlet system at two conditions; when the surface temperature is lower than the dew point temperature of the static air in the inlet system and when the surface temperature is below freezing point. As long as the surface temperature is above the dew point temperature, condensation will not occur and ice will not form even if the surface temperature is below the freezing point temperature.

The icing conditions regions have been demonstrated for different velocities in the inlet system. It was apparent that highest hazard of the glaze ice coincides at air velocity 150 [m/s] and ambient conditions between -10 [$C^o$] and 3[$C^o$] and relative humidity at or above 98%. To avoid the ice formation in the inlet system of the gas turbine it is not necessary to heat the incoming air to the compressor until surface temperature becomes higher than the freezing point temperature. It's only necessary to heat the ambient air just to the level that makes the surface temperature higher than the dew point temperature of the static air. It is perceptible that this will require less heat used to avoid ice formation in the compressor inlet.

Compressor bleed anti-icing system has a greater influence on gas turbine performance than hot water heat exchanger system. With both the systems some cycle performance is lost since the inlet air is heated to a higher - and more unfavourable - temperature. The difference is that while the hot water heat exchanger system uses hot water from the process which is a free or cheap source of heat the compressor bleed system extracts air that has been compressed using the available turbine work. Thus the loss of available power output and cycle efficinency to avoid ice formation is greater when using the compressor bleed system than when using the hot water heat exchanger.

Ice sensors are very important in detecting ice formation in the compressor inlet. With help of ice sensors, the anti-icing system can be activated only when ice is present in the compressor inlet. This will reduce the heat power required to avoid ice formation even further. It was fond that the most likely place for condensate ice to occur is somewhere between bellmouth and IGVs.

# 13. Future developments in Siemens

The subject of this master thesis is very wide and there are many areas that could be developed. Icing mechanisms, factors effecting icing and anti-icing systems have been investigated earlier in aero-engines and for aircraft wings. It is of utmost importance for aero-engines to avoid ice formation since it can leads to fatal consequences. Icing in stationary gas turbines hasn't been investigated as widely and deeply as aero-engines. As a result, there is a lot of work that can be done in this field. Some systems that are used in aero-engines such as the components heating system may also be applied in stationary gas turbines. This system should be investigated and tested in stationary gas turbines.

During my thesis a lot of ideas came to me that would have been very interesting to investigate further and may be of interest for Siemens Industrial Turbomachinery AB, Finspång to spin on. There are simple ideas of how the anti-icing system may be improved.

- The recovery factor is a very important factor in the icing conditions calculations. During my master thesis in Siemens there was an attempt to measure the surface temperature in 25 points in the inlet system of the compressor but due to lack of time this was not performed. It would be interesting to do so as to obtain the surface temperature.
- I recommend studying different anti-icing systems and the possibility of applying them in the Siemens gas turbines. The study can include the technical part and the economical part. It will be interesting to know which of these systems is most economical.
- Studying the sensor placing in the inlet system of the compressor while taking into account the air aerodynamic flow is a very interesting approach. Another question is how the sensor affects the air aerodynamic in order to figure out the most suitable place for the sensor.
- Design a control system to activate the anti-icing system in an effective way. This control system would respond to the present icing conditions in the inlet of the gas turbine and activate the anti-icing system.
- Implementing this literature study by checking out my findings in the icing conditions. This can be accomplished either by doing a small scale test or by comparing my result with data from Siemens gas turbines that operate in arctic environments.
- In this master thesis the precipitate icing was not taken into account since it is difficult to predict water droplets trajectories in the compressor inlet [37]. It will be useful to investigate the icing in the Siemens gas turbine as a result of precipitate icing.

# References

[1]. UNUS A. CENGEL & MICHAEL A. BOLES, THERMODYNAMICS, FOURTH EDITION, 2002, ISBN 0-07-238332-1.

[2]. HIH Saravanamutto, CFC Rogers & H Cohen, Gas Turbine Theory, FIFTH EDITION, ISBN 0130-15847-X, 2001.

[3]. Richard W. Johnson, The Handbook of Fluid Dynamics, Chapter 40, 1998, ISBN: 0849325099.

[4]. B. S MASSFY, Mechanics of fluids, Third Edition, 1975, ISBN: 0 442 300212.

[5]. ASCHER H. SHAPIRO, The Dynamics and Thermodynamics of compressible fluid flow, Vol I+II, 1954.

[6]. Terry T. Lankford, Aircraft Icing, PRACTICAL FLYING SERIES, ISBN 0-07-134139-0, 2000.

[7]. Ernst R. G. Eckert, Survey of Boundary layer Heat Transfer at High Velocities and High Temperatures, University of Minnesota, April 1960.

[8]. R. J. MONAGHAN, M.A., A Survey and Correlation of Data on Heat Transfer by Forced Convection at Supersonic Speeds, MINISTRY OF SUPPLY, AERONAUTICAL RESEARCH COUNCIL, 1958.

[9]. Magnus Genrup, On Degradation and Monitoring Tools for Gas and steam Turbines, Doctoral Thesis, Department of Heat and power Engineering, Lund Institute of Technology, Lund University, Sweden, 2005.

[10]. Chin-Hsiang Cheng & Keng-Hsien Wu, Observation of Early-Stage Frost Formation on a Cold Plate in Atmospheric Air Flow, Journal of Heat Transfer, ASME, February 2003, vol 125, p 95.

[11]. G. F. Naterer, Temperature Gradient in the Unfrozen Liquid Layer for Multiphase Energy Balance with Incoming Droplets, ASME, February 2003, vol 125, p 186.

[12]. LASSE MAKKONEN, Models for the growth of rime, glaze, icicles and wet snow on structures, THE ROYAL SOCIETY, 2000, p 2913-2939.

[13]. Guy Fortin, Jean-Louis Laforte & Arlene Beisswenger, Prediction of Ice Shapes on NACA0012 2D Airfoil, Anti-icing Materails International Laboratory, Universite du Quebec a Chicoutimi, 2003-01-2154.

[14]. Mats Blomqvist, Inloppsfilter till gasturbiner, VärmeForsk, Stiftelsen för värmeteknisk forskning, 1995-01-17.

[15]. Frank W Muscroft, Static or pulse clean: which is best?, EMW Filtertecknink, Diez, Germany, Modern power systems, December 2003, p19.

[16]. M.C. MANNA & H. von E.DOERING & J. R. PATTERSON, Experience and Application of Gas Turbine Inlet Air Filters, ASME, 75-GT-105.

[17]. T. J. Retka & G. S. Wylie, Field Experience With Pulse-Jet Self-Cleaning Air Filtration on Gas Turbines in an Arctic Environment, Journal of Engineering for Gas Turbines and Power, January 1987, vol 109, p 79.

[18]. D. G. T. HILL, Gas Turbine Intake Systems in Unusual Environments, ASME, 73-GT-38.

[19]. CECIL H. GOULDING & MYRON G. RASMUSSEN & FREDERICK M. FRITZ, JR., Technical and Other Considerations for the Selection of Inlet Air Filteration Systems for High-Efficiency Industrial Combustion Turbines,

ASME, 90-GT-176. Presented at the Gas Turbine and Aeroengine Congress and Exposition-June 11-14-1990, Brussels-Belgium.

[20]. T. Jaroszczyk & J. Wake & M. J. Conner, Factors Affecting the Performance of Engine Air Filters, Journal of Engineering for Gas Turbines and Power, October 1993, vol 115, p 693.

[21]. D.S.T. Raubenheimer, Selection and Operation of Gas Turbine Air Filters, Turbomachinery International, Jan/Fab 1990, p 26.

[22]. A. W. Anderson & R. G. Neaman, Field Experience with Pulse- Jet Self-Cleaning Air Filteration on Gas Turbines in a Desert Environment, ASME, 82-GT-283.

[23]. L.L. HSU, Total Corrosion Control for Industrial Gas Turbines: Airborne Contaminants and Their Impact on Air/Fuel/Water Management, ASME, 1988, p 11.

[24]. R.L. Loud & A. A. Slaterpryce, Gas Turbine Inlet Air Treatment, GE Power Generation.

[25]. L. CUVELIER & M. D. BELCHER, A New Air System Concept for Space Limited Applications and Retrofits, ASME, 90-GT-177.

[26]. David Brumaucgh, Inlet Air Filteration Adapts to Evolving Gas Turbine Technology, Power Engineering, October 2002.

[27]. F. ARVIDSSON, Operating Experience with Gas Turbines under Arctic and tropical Conditions, ASME, 67-GT-30.

[28]. L.L. HSU, Total Corrosion Control for Industrial Gas Turbines: Airborne Containments and Their Impact on Air/Fuel/Water Management, ASME, 88-GT-65.

[29]. Deciréé Engmark, Airborne contaminants and their impact on gas turbines, Linköping Univerity, Department of Chemical Engineering, 26-08-2004.

[30]. J. W. Freestone and M. Weber, An Industrial Sensor for Reliable Ice Detection in Gas Turbines, Department of Machinery Monitoring and Diagnostics, Vibro-Meter SA, Fribourg, Switzerland, ASME, 1994, vol 9, p 463.

[31]. William E. Stewart, Jr., Ph.D.,P.E., Condensation and Icing in Gas Turbines Systems: Inlet Air Temperature and Humidity Limits, ASHRAE Transactions:Symposia, AT-01-15-3, 2000, p 887.

[32]. William E. Stewart, Jr., Ph.D.,P.E. & Anthony B. Parrack, Air Temperature Depression and Potential Icing at the Inlet of Stationary Combustion Turbines, ASHRAE Transactions:Symposia, 4401(RP-1019), 2000, p 318.

[33]. Gillingham, G.R., New System for Preventing Icing of Gas Turbines Inlets, ASME, n 76-GT-84, 1976.

[34]. Kovacs, P. & Stoff, H., Icing of Gas Turbine Compressors and Ways of Achieving Uninterrupted Operation, Brown Boveri & Co, Gas & Steam Turbine Dep, Stafa, Switz, vol 72, n 4, 1985, p 172-177.

[35]. Bagshaw, K. W., Icing Problems-Review of Simulated Ice Ingestion Tests, ASME, n 76-GT-128, 1976.

[36]. Chappell, M. S. & Grabe, W., Icing Problems on Stationary Gas Turbine Powerplants, ASME, 1974.

[37]. Mann, D.L. & Tan, S.C. & Pugh, C.G. & Hobbs, J. R., Ice accretion prediction for gas turbine intake systems, International Symposium on Air Breathing Engines, 1991, p 1159.

[38]. Dickson,J., EXTREME- COLD- WEATHER OPERATION OF GAS_TURBINES SHOWS KEY PROBLEMS, Oil and Gas Journal, vol 74, n 17, 1976, p 104-110.
[39]. Calvert, Winter, Prevent damage to gas turbines from ice ingestion, Power, vol 138, n 10, 1994, p 73-75.
[40]. Willbanks, C. E. & Schulz, R. J., ANALYTICAL STUDY OF ICING SIMULATION FOR TURBINE ENGINES IN ALTITUDE TEST CELLS, Journal of Aircraft, vol 12 ,n 12, 1975, p 960-967.
[41]. Vasudev,S:A & Balmukund Vasani & Meera Kaushal, HEAT TRANSFER ANALYSIS OF A HEASTING SYSTEM FOR ANTI_ICING OF AIRCRAFT ENGINES.
[42]. Air Inlet system, GE Marine and Industrial Engines, 1997.
[43]. Theory of Air-Conditioning, www.maritime.org/fleetsub/refrig/chap16.htm, 03-02-2006.
[44]. Dr. Dave Dempsy, Water Vapor and Clouds, Dept. of Geosciences, www.ar-tiste.com/ThermoOfFog2.html, 03-02-2006.
[45]. Wikipedia, the free encyclopedia, http://en.wikipedia.org/wiki/Main_Page, 02-02-2006.
[46]. Kenith C. Heidorn, PhD., Weather Phenomenon and Elements, Hard Rains WillFall2000,http://www.islandnet.com/~see/weather/elements/hardrain.htm,02-02-2006.
[47]. ATMOSPHERIC PHENOMENA, CHAPTER 5 http://www.gvc.gu.se/ngeo/deliang/14312_ch5.pdf, PDF, 02-02-2006.
[48]. Aviation Weather, http://virtualskies.arc.nasa.gov/weather/tutorial/tutorial1.html, 02-02-2006.
[49]. Grant W. Petty, Depertment of earth & Atmospheric Sciences, Purdue University,http://www.yarchive.net/physics/water_droplet_nucleation.html, 02-02-2006.
[50]. Saturation Vapour Pressure above a Solution Droplet, Appendix C, http://www.mpimet.mpg.de/~banse.dorothea/Writings/DFB_diploma_app3.pdf ,PDF, 02-02-2006.
[51]. Collection Efficiency for Icing Analysis http://www.fluent.com/solutions/examples/img/ex156.pdf, PDF, 02-02-2006.
[52]. The atmosphere, the weather and flying, Icing, Chapter 12, Environment Canada, http://www.mscsmc.ec.gc.ca/education/aware/chapter_12_e.cfm, 02-02-2006.
[53]. Aircraft Icing Handbook, http://www.caa.govt.nz/fulltext/safety_booklets/aircraft_icing_handbook.pdf, PDF, 02-02-2006.
[54]. Aviation Weather Hazards, Chapter 2, http://www.navcanada.ca/ContentDefinitionFiles/publications/lak/OnQc/2-OQ33E.PDF, 02-02-2006.
[55]. Dr. Johan Grohols, Psych Central ,http://www.psychcentral.com/psypsych/Freezing_rain, 02-02-2006.
[56]. Icing Type and Severity, Section Summaries, http://meted.ucar.edu/icing/pcu6/summary.htm#icetype, 02-02-2006.
[57]. Codes and Scales, http://www.coolweather.co.uk/htdocs/codesandscales.htm, 02-02-2006.
[58]. GLOSSORY OF METROLOGY, http://amsglossary.allenpress.com/glossary, 02-02- 2006.

[59]. Weather.com, http://www.weather.com/glossary/s.html#st, 02-02-2006.
[60]. Windows to the universe, Clouds Types, http://www.windows.ucar.edu/tour/link=/earth/Atmosphere/clouds/cloud_types.html, 02-02-2006.
[61]. Surface Tension and Bubbles, Hyperphysics, http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html, 02-02-2006.
[62]. York Snow, Science of making snow, http://www.windows.ucar.edu/tour/link=/earth/Atmosphere/clouds/cloud_types.html, 02-02-2006.
[63]. Glossary of Meterological Terms, http://www.psicompany.com/weather/wxterm.pdf , PDF, 02-02-2006.
[64]. Atmospheric Moisture, http://www.met.tamu.edu/class/Metr201/Ch5AtmosphericMoisture.html, 02-02-2006.
[65]. GDS-II Filtration System, Donaldson, http://www.donaldsonfilters.com.au/library/library.asp?intT1ID=5, 02-02-2006
[66]. Wheelabrator Air Pollution Control Inc. Cartridge Dust Collectors http://www.donaldsonfilters.com.au/library/library.asp?intT1ID=5, 02-02-2006
[67]. GDX, Donalson http://www.donaldsonfilters.com.au/library/library.asp?intT1ID=5,02-02-2006
[68].Compressor Washing, Turbotect, http://www.turbotect.com/lib/CC-Article-Combined-Cycle-Journal-2004.pdf, PDF, 03-02-2006.
[69]. Ice Protection Control Systems, Hamilton Sundstrand, A United Technologies Company, Dynamic Controls, http://www.hamiltonsundstrandcorp.com/Files/Hamilton_Sundstrand/Local/US-en/ourcompany/HS_&_DCHS_Overview_-_ICE.pdf, PDF, 03-02-2006.
[70]. Hongchang Electric Heater Products Factory, http://images.google.com/imgres?imgurl=http://www.chinesesource.com/products/el_co_hongchang03.jpg&imgrefurl=http://www.chinesesource.com/company.cfm%3Fcompanyid%3D7955&h=160&w=200&sz=9&tbnid=4Iv5VFHh5GsJ:&tbnh=79&tbnw=99&hl=sv&start=130&prev=/images%3Fq%3Dcomponent%2Bheating%2B%26start%3D120%26svnum%3D10%26hl%3Dsv%26lr%3D%26sa%3DN, 03-02-2006.
[71]. Ice Meister Model 9732-OEM, Technical Data Sheet, New Avionics CORPORATION, By Mail, 01-02-2006. http://www.newavionics.com/ , 03-02-2006.
[72]. Protection and Condition Monitoring of the LM2500 Gas Turbine, http://www.skfcm.com/service/support2/New%20Library/CM3081%20LM2500%20Gas%20Turbine.pdf, PDF, 03-02-2006.
[73]. Rosemount Icing Detector, http://www.eol.ucar.edu/raf/Bulletins/B24/iceProbe.html, 03-02-2006.
[74]. Vibro-Meter, Industrial and Marine, http://www.vibro-meter.com/industrial/sensors-other.html, 03-02-2006.
[75]. Freezing Point Depression in Solutions, Hyperphysics, http://hyperphysics.phy-astr.gsu.edu/hbase/chemical/meltpt.html, 02-02-2006.
[76]. Freezing Point Depression, http://members.aol.com/profchm/fpdepres.html, 02-02-2006.
[77]. Freezing Point Depression, Wikipedia, the free encyclopedia, http://en.wikipedia.org/wiki/Freezing_point_depression, 02-02-2006.

[78]. Pro. Michael Tjernström, Department of Meteorology, Stockholm University , Sweden, http://www.misu.su.se/

[79]. http://images.google.com/imgres?imgurl=http://www.kiltechunderwater.com/bluebird/Diaryarc/photos/rebuildPhotos/blades.jpg&imgrefurl=http://www.kiltechunderwater.com/bluebird/Diaryarc/photos/September_December.htm&h=270&w=360&sz=37&tbnid=bmN-gmW-rPQJ:&tbnh=87&tbnw=117&hl=sv&start=35&prev=/images%3Fq%3Dcorrosion%2Bblades%26start%3D20%26svnum%3D10%26hl%3Dsv%26lr%3D%26sa%3DN, 03-02-2006.

[80]. Industrial air solutions http://images.google.com/imgres?imgurl=http://www.industrialairsolutions.com/images/DFO_pulse-pressure.gif&imgrefurl=http://www.industrialairsolutions.com/dust-collectors/cartridge-downflo-oval.htm&h=278&w=384&sz=19&tbnid=bQnok2AIYUIJ:&tbnh=86&tbnw=119&hl=sv&start=68&prev=/images%3Fq%3Dpulse%2Bfilter%26start%3D60%26svnum%3D10%26hl%3Dsv%26lr%3D%26sa%3DN, 03-02-2006

[81]. http://europa.eu.int/comm/energy_transport/atlas/htmlu/ccpg.html03-02-2006

[82]. http://en.wikipedia.org/wiki/Combined_cycle03-02-2006

[83]. http://images.google.se/imgres?imgurl=http://www-das.uwyo.edu/~geerts/atsc2000/hw/hw3_files/image002.jpg&imgrefurl=http://wwwdas.uwyo.edu/~geerts/atsc2000/hw/hw3.htm&h=629&w=864&sz=89&tbnid=QifmI2PEpgJiwM:&tbnh=104&tbnw=144&hl=sv&start=88&prev=/images%3Fq%3DPSYCHOMETRIC%2BCHART%26start%3D80%26svnum%3D10%26hl%3Dsv%26lr%3D%26sa%3DN 03-02-2006

[84].www.industrialairsolutions.com, 03-02-2006

[85]. Siemens gas turbines brochures