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Anti-icing system at gas turbine compressor bell-mouth and Inlet Guide Vane (IGV)

Farshad Matbou[a], Hadi Alahyari[b], Fateme Namvar[c]

[a] *Master of Mechanical Engineering, Sharif University of Technology, Tehran ,Iran.*

[b] *Technical proposal & Mechanical expert, Engineering Deputy of Power Division in MAPNA Group, Tehran, Iran.*

[c] *Graduate of Petrochemical engineering, Shiraz University, Tehran ,Iran.*

Abstract

Anti-icing system is generally used in order to prevent ice formation at gas turbine compressor bell-mouth and inlet guide vanes (IGV) in cold climates, which is caused by air pressure drop and velocity rise and consequent mechanical damage and performance deterioration. Ice formation at the compressor bell-mouth and on the inlet guide vanes is depended on variant parameters including: ambient air temperature, relative humidity of the environment, air velocity at compressor bell-mouth and IGV and metal surface temperature of ice formation location. In two frequent conditions ice may be formed; 1-water droplet existence in liquid or solid phase and in the shape of snow, rain and other precipitations. 2-Existence of vapor condensation in inlet air way that is because of temperature depression and velocity rise. Anti-Icing system by which extracting of hot gas from mid/last-stage of compressor (this method is the most popular methods for anti-icing system), increase inlet air temperature till inlet air in bell-mouth and IGV location gets far from ice forming condition. Extraction of air from compressor is caused performance degrading of gas turbine approximately 2~5% in power and 1~2% in efficiency depend on extracted flow rate. So accurate determination of operation limit of Anti-Icing system has great effect on gas turbine performance and its fuel consumption.

Keywords: Anti-icing system, gas turbine compressor Ice formation, hot gas, performance degrading

Introduction:

One of the most important objectives for gas turbines is ice forming especially in downstream of filter house where can't be observed easily.

In [1] it is shown how new limits can be derived based on ice accretion thermodynamics at stationary and rotating surface of compressor.

Ice in two frequent conditions can be formed; 1-water droplet existence in liquid or solid phase and in the shape of snow, rain and other precipitations. 2- Existence of vapor in inlet air somehow this vapor due to air stream acceleration into high velocity in the downstream of the filter house is condensed and ice can be built up. This results in a static temperature depression of 15 °C or even more. It depends on air velocity in different sections of inlet duct. Generally gas turbines are equipped with hoods and filters in their air intakes, these pieces of equipment prevent and

omit ice particles, so at the first mentioned condition (i.e. precipitation related particles) ice particles can't be harmful for gas turbines except in the conditions, in which, because of heavy precipitations, the bird screen of the gas turbines air intake causes clogging and ice formation at upstream of the filters [2].

Be informed that the philosophy of anti-icing is preventing of ice formation downstream of filters and compressor bell-mouth. So in the present anti-icing logic in some manufacture's product there is also a low temperature limit, because in very low temperatures there is no possibility for ice formation in air intake and air humidity enter to compressor in the shape of very little particles with no damaging effect on compressor posterior blades [3].

Due to air stream acceleration and its high velocity in inlet duct, vapor condensation downstream of filtration system and at compressor inlet is unpreventable. If vapor condensation is not prevented by ice formation in bell-mouth and IGV, inlet area in this situation will decrease and consequently inlet velocity increase therefore pressure drop and mass flow rate decrease. For each turbine depending on its compressor upstream velocity, ice formation can initiate in a special range of temperature and relative humidity and then cause power decrease, surge possibility increase and compressor blades damages. In **Error! Reference source not found.** different kind of ice formation in different location of inlet duct and their probabilities are shown.

Table 1: Ice accumulation tendencies in air intake system [3]

Section No.	*Precipitate Icing*				*condensate Icing*		
Intake Components	**Hail**	**Ice Crystals**	**Snow**	**Freezing rain**	**Hoarfrost**	**Rime Ice**	**Glaze Ice**
Inlet Hoods	**1**	**1**	**1**	**1**	**1**	**1**	**1**
Filters	**1**	**2**	**2**	**1**	**4**	**2**	**2**
Plenum Chamber	**1**	**1**	**1**	**1**	**2**	**2**	**2**
Bell-mouth	**1**	**1**	**1**	**1**	**4**	**4**	**3**
Struts	**1**	**1**	**1**	**1**	**4**	**4**	**3**
Inlet Guide Vane (IGV)	**1**	**1**	**1**	**1**	**4**	**4**	**3**
First stage compressor	**1**	**1**	**1**	**1**	**2**	**2**	**2**
Possibility:	1 Non	2 Small	3 Moderate	4 Strong			

Research methodology

There should be two conditions for ice to be formed; 1-The temperature of metal surface should be below the air dew point temperature, in order to form condensation. 2-The temperature of metal surface should be below the freezing point of water i.e. 0 °C.

In order to investigate ice formation possibility at compressor bell-mouth and pass way, air velocity and Recovery Factor (RF) at different location of compressor upstream duct shall be calculated precisely.

The metal surface temperature is generally greater than the fluid temperature passing over it. That is because of boundary layer and friction. This temperature difference is depended on metal and fluid specifications including fluid Prandtl number.

Prandtl number of air is reported between 0.8 and 0.9 in different references. Based on experimental results Recovery Factor (RF) is as follows [3]:

For laminar flows: $RF = \sqrt{Pr} \rightarrow RF = 0.85$ (1)

For turbulent flows: $RF = \sqrt[3]{Pr} \rightarrow RF = 0.87 - 0.9$ (2)

Measurements for a subsonic turbulent flow (Mach=0.3 to 1) indicate that RF is between 0.87 and 0.91 (as indicated in Figure 1.

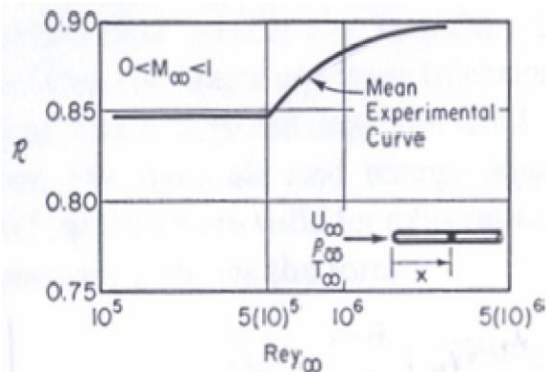


Figure 1: the measurement recovery factor [4]

Equations (1) and (2) are used to calculate the RF based on air temperature, static temperature , specific heat capacity at constant pressure (C_p) , air velocity and surface temperature of metal.

$$RF = \frac{T_{wa}-T}{T_0-T} \rightarrow \frac{T_{wa}-T}{V^2/2gC_p} \quad (3)$$

$$RF = \frac{\frac{T_{wa}}{T}-1}{V^2/2C_p} = \frac{\frac{T_{wa}}{T}-1}{\frac{k-1}{2}M^2} \quad (4)$$

In them,

T_{wa}, is the surface temperature

T_0, is the stagnation or ambient temperature

T, static or bell-mouth temperature

M, is the Mach number

C_p, is heat capacity at constant pressure

V, is the air velocity

RF, is recovery factor

For example using the equations (3) and (4) the surface temperature of IGV and the amount of temperature drop in SOLAR MARS 100 gas turbine at T_{air} of 40°F are calculated [3] [5]. In this gas turbine, using manufacturer data nominal flow rate is about 41.3 Kg/s. According to IGV dimensions the air velocity at the inlet of gas turbine compressor is about 197 m/s or 646 ft/s. Therefore the temperature drop in IGV bell-mouth will be calculated as 19.3 °C. Detailed calculations is as follow;

$$T_0 = T + \frac{V^2}{2C_p g} \quad (5)$$

$$40 = T + \frac{646^2}{2\times186.72\times32.2} \Longrightarrow T = 5.2\ ^\circ F = -14.9\ ^\circ C \quad (6)$$

$$RF = \frac{T_{wa}-T}{T_0-T} \Longrightarrow 0.8 = \frac{T_{wa}-(-14.9\ ^\circ C)}{19.4\ ^\circ C} \Longrightarrow T_{wa} = 0.6\ ^\circ C \quad (7)$$

Where;

Cp=186.72 ft.lb/lbm.°F, specific heat of air at 40°F

g=32.2 ft/s^2, standard acceleration of gravity

According to the above mentioned calculations, the temperature drop of IGV surface, the most probable location of ice formation, is equal to 3.8°C ([[40°F-32]/1.8]-0.6°C=3.8°C).Referring to Psychometric chart for the ambient air temperature of 3.8 °C and the pressure of 101.325 kPa, the air dew point is 0°C for about 76% relative humidity. So for the air temperatures below 3.8°C and relative humidity above 76% ice formation is highly probable in SOLAR MARS 100 gas turbine. Also there is another equation for calculating of surface temperature of IGV, represented by

SOLAR Company. This equation is a little difference from equations (3) and (4). Because of using Prandtl number the results have approximate values.

$$T_w = T_0 - T_0\left(1 - \sqrt{P_N}\right)\left(1 - \frac{2}{M^2(k-1)+2}\right) \qquad (8)$$

Where;

k is Specific heat ratio for air (1.4)

P_N is the Prandtl number

M is the Mach number

T_0 is ambient temperature

T_w is wall temperature

For the previous solved example and P_N=0.72 we have;

$$M = 0.6$$

$$T_w = 277.4 - 277.4\left(1 - \sqrt{0.72}\right)\left(1 - \frac{2}{0.6^2(1.4-1)+2}\right) \Longrightarrow T_w = 1.6\ ^\circ C \qquad (9)$$

Result and The Analysis of Data

We MGT 70 (V94.2) gas turbines were installed and operate in many different areas in the world with various environments such as tropics, deserts and in coastal environments. In cold and humid environments many problems can appear during operation periods. (A simple cycle plant view of MGT 70 (V94.2) is shown in Figure 2: MGT 70 (V94.2) simple cycle power plant and ancillary and prepared by MAPNA [4]Figure 22.)

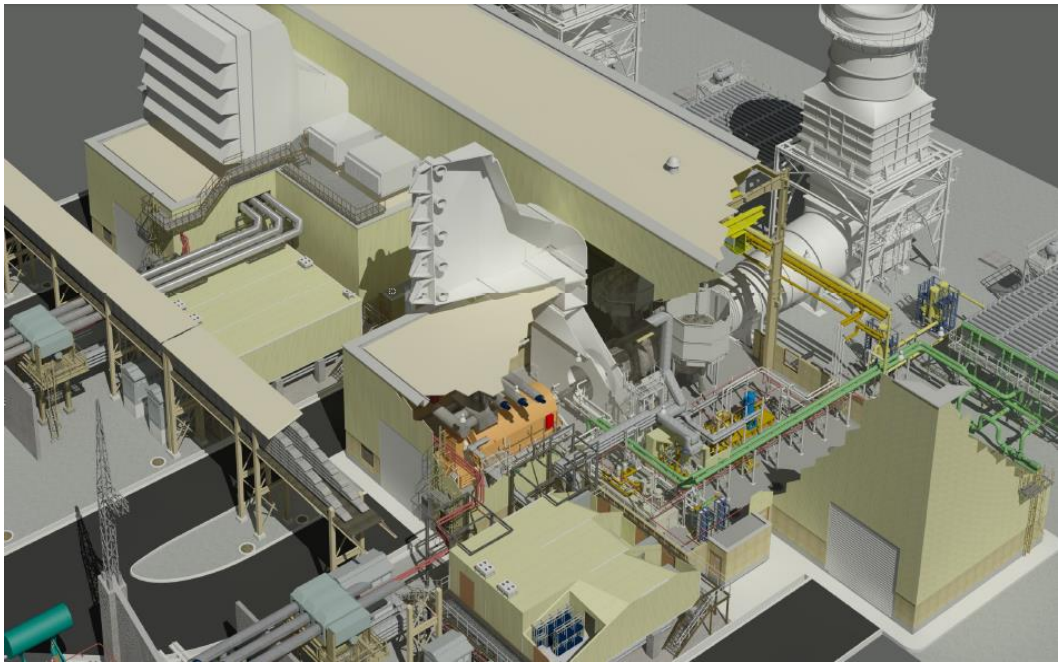


Figure 2: MGT 70 (V94.2) simple cycle power plant and ancillary and prepared by MAPNA [4]

Air velocity in gas turbine compressors IGV is in the range of 150-270 m/s and based on MAPNA reports, for MGT 70 (V94.2) gas turbine it is as presented in **Table 1**.

Table 1 :Inlet air velocity at different position of IGV in MGT 70 (V94.2) gas turbine

	Fully open				Fully close
IGV position	0	10	20	30	40
Max. velocity	176	164	152	135	114
Average velocity	169	157	145	128	105

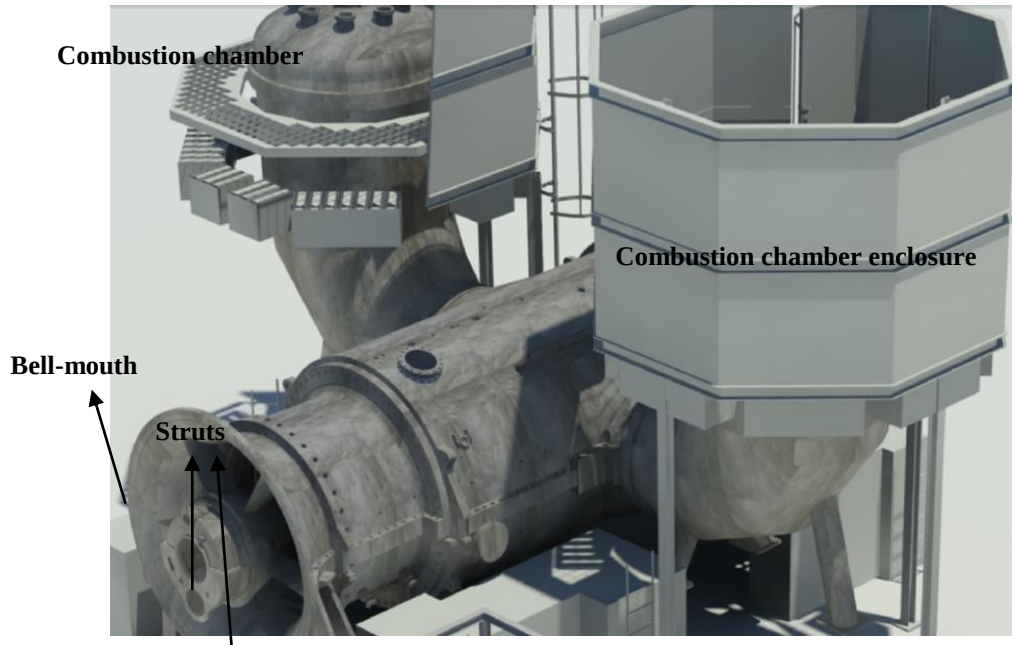


Figure 3 :MGT 70 (V94.2) gas turbine prepared by MAPNA [4]

Based on Table *1 :Inlet air velocity* at different position **of IGV in MGT 70 (V94.2) gas turbine**

	Fully open				Fully close
IGV position	0	10	20	30	40
Max. velocity	176	164	152	135	114
Average velocity	169	157	145	128	105

data the maximum inlet air velocity for MGT 70 (V94.2) gas turbine is 176 m/s. For this velocity value if the ambient temperature is 5°C, compressor inlet air temperature will be -10.4°C as below calculation.

$$5 = T + \frac{176^2}{2(1004)} \Longrightarrow T = -10.4\ ^\circ C \qquad (10)$$

Generally for the air velocity of 176m/s the difference between stagnation and static temperatures will be 15.4°C. Using the following relations the ambient temperature at which the IGV surface temperature becomes 0°C, will be 2.98°C.

$$RF = \frac{T_{wa} - T}{T_0 - T} \Longrightarrow 0.8 = \frac{0 - (T_0 - 15.4\ ^\circ C)}{15.4\ ^\circ C} \Longrightarrow T_0 = 2.98\ ^\circ C \qquad (11)$$

As previously mentioned for ice formation another condition is also needed rather than having under zero IGV surface temperature i.e. dew-point temperature should be also more than IGV surface temperature. Thus for the case in which the ambient air temperature is 2.98°C and the dew point temperature is more than IGV surface temperature, ice formation phenomena on IGV surface will be probable.



Figure 1: MGT 70 (V94.2) gas turbine IGV and Struts permission from MAPNA [4]

For MGT 70 (V94.2) gas turbine at different IGV positions and ambient air temperatures, the IGV surface temperature and ambient air dew point is calculated and based on the two previously mentioned conditions, the ice formation area is determined and indicated in Figure 2.

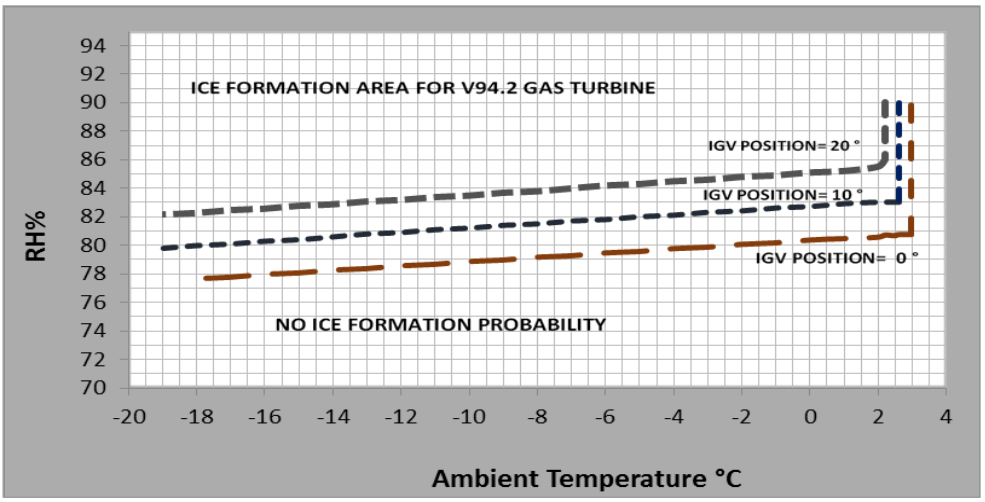


Figure 2: Ice formation area for MGT 70 (V94.2) gas turbine

In order to estimation of dew point temperature for different conditions Magnus [2] relation (equation 12) is used. This relation is valid for the temperature range of -45°C to 60 °C with Magnus parameters of λ and β equal to 243.12 and 17.62 respectively.

$$Dp(T,RH) = \frac{\lambda\left(\ln\left(\frac{RH}{100}\right)+\frac{\beta T}{\lambda+\beta}\right)}{\beta-\left(\ln\left(\frac{RH}{100}\right)+\frac{\beta T}{\lambda+\beta}\right)} \quad (12)$$

Using equations(3) and (4) for calculating the IGV surface temperature and dew point temperature of ambient air, regarding to previously mentioned explanations ice-formation conditions can be detected as shown in Figure 2. In primary control logic of MGT 70 (V94.2) anti-icing setting has been appointed when ambient air condition arrives to ±5 C and 60% relative humidity simultaneously. But this setting is imprecise and impact on gas turbine power output for about 5~8 MW and efficient about 1~2% regarding to ambient air condition [6]. In MGT 70 (V94.2) gas turbine the anti-icing system is constituted of a circuit of compressed air at high temperature (350~380^{o}C) from the last stage of the gas turbine compressor, it has the function of increasing the inlet air temperature of about 5 ^{o}C (in respect of inlet air temperature) when ambient air condition arrives above mentioned situation. Extracted hot air (350~380 ^{o} C and 7 to 10 bar and up to 15 kg/s) from last-stage of compressor is passed through one shut off valve and one control valve and is injected before insect screen meshes. In this arrangement when air condition is arrived to ±5^{o}C and 60% relative humidity simultaneously, shut off valve get open and control valve regarding inlet air condition, regulate extracted air flow till inlet air temperature after insect screen increase to +5 °C. As mentioned before, this setting is a conservative and imprecise. According to Figure 2 MGT70 anti-icing system setting can be modified as below. In this modification, humidity can be set linear function that varies with temperature. With this modification power is improved and fuel consumption for specific power output is decreased.

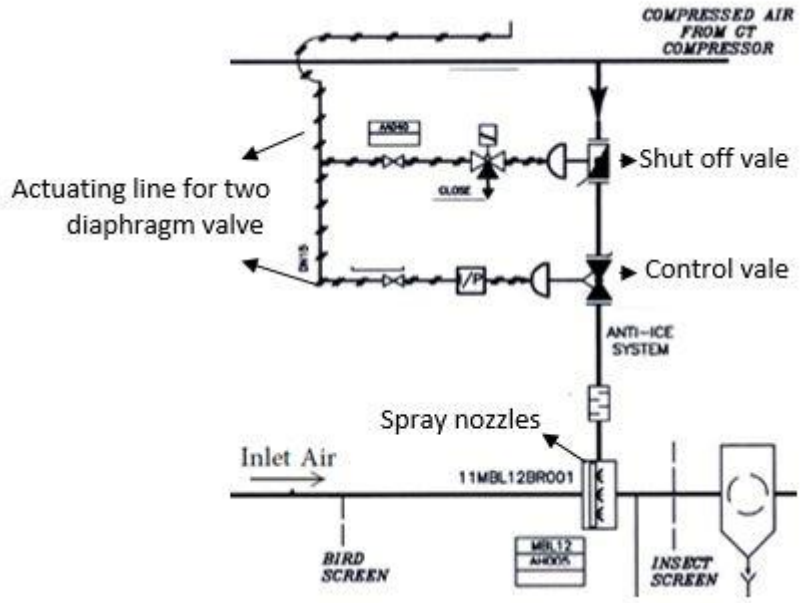


Figure 3: MGT 70 (V94.2) Anti-Icing P&ID prepared by MAPNA [4]

Research Findings

First Referring to Figure 2 in MGT 70 (V94.2) gas turbine in base load (IGV is fully open) Ice can build up in IGV surface if ambient air temperature is below 2.98 °C, but corresponding relative humidity for ice formation varies with respect to ambient air temperature . This variation is very slightly meaning that for wide range of ambient air temperature it can be consider constant. For this reason in base load operation and sea level for upper limit of anti-icing system it can be selected +3 °C for temperature and 80% for relative humidity. In some references it has been mentioned that in very cold condition the vapor in the inlet air converts to rime ice very rapidly which has low adhesive properties and it is brittle and easier to remove than glazed ice [3]. Therefore in IGV control logic some manufactures like SIEMENS set lower operation limit for anti-icing system. Also for simplifying anti-icing control logic it can be set +3 °C for temperature and 77% relative humidity for wide range of ambient air condition regardless humidity variation. In this setting operator is assured that gas turbine operate in cold climate without ice forming or remarkable gas turbine performance loss.
GE manufacture has selected below (Figure 4) operation limit for its gas turbine that has good compatibility with this calculation and proposed graph. Some difference such as ice formation limit between these two figures (Figure 2 and Figure 4) is due to different inlet air velocities.

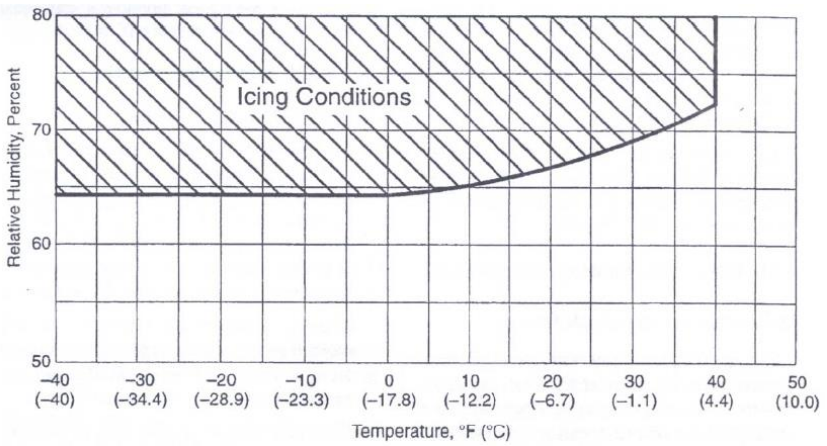


Figure 4: Ice formation area for GE's gas turbine [7]

Conclusion:

In the gas turbines anti-icing system is used to eliminate ice formation in inlet path of gas turbines. Most popular method for anti-icing system is extraction of hot air from last stage of compressor. Extracting hot air from compressor derate gas turbine's performance around 5-8% and decrease efficiency of gas turbine around 1-2%. So accurate determination of operation time of this system can affect on gas turbine performance greatly. In early mgt70 gas turbine's anti icing system, operate in +_5 c and 60% relative humidity. But in this paper was demonstrated that more accurate condition is +3 c and relative humidity

more than 77% in wide range of operation conditions. So with accurate determination of icing condition and implement it in gas turbine's anti icing logic can gain about 8Mw.

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