Fundamental Study on Jet Defrosting Method for Precooled Turbojet Engines (Effects of the Surface Temperature of Cooling Tubes)

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Abstract

Fundamental experiments with single row heat exchanger were conducted for the purpose of validating new defrosting method using jet impingement. The coolant temperature were varied from 83 to 250 K. We used the jet periodically, once in 50 second and the duration of the jet is 0.1 second. The effect of the coolant temperature in the effectiveness of the jet defrosting was investigated.

Introduction

Precooled turbojet engines are the engines which have heat exchangers to cool the breathed air with its cryogenic fuel, such as liquid hydrogen or LNG. The purpose to cool the air is to protect the engine against aerodynamic heating when it is used at hypersonic condition. In addition to that, the precooled cycle is useful to improve the cycle performance. However, a problem has arisen in the development of the precooled turbojet engine that frost formation on the cooling tubes of the precooler (heat exchanger) prevents us from cooling the air. The frost also increases the pressure loss of the precooler. We have to solve the frost formation problem to develop and use precoolers in flight.

Some researchers have tried to solve this frost formation problem. Especially the idea by Harada et al.[1)], and Kimura et al.[2)] using alcohol spray have been succeed in removing the frost. However, these ideas need to bring alcohol and the spraying system, which causes the increase in the mass of the engine. Another method often used to remove frost is to use redundant system. Two heat exchangers are prepared and usually only one of those is used. When much frost builds up on the cooling tubes, we stop using the heat exchanger and start to use the other one. However, this redundant system needs two heat exchangers, which also cause mass increase.

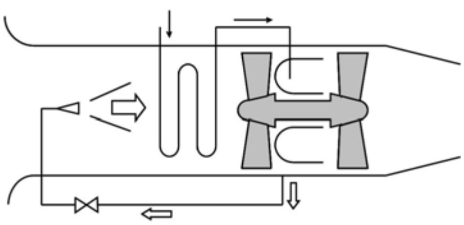


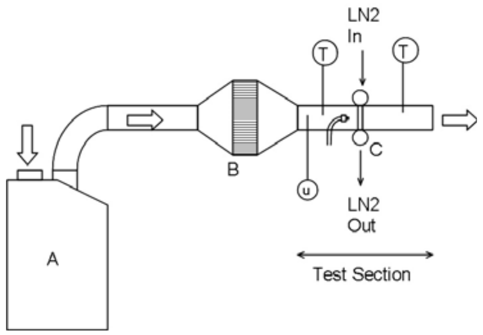
Fig.1 Schematic diagram of the precooled turbojet engine system with the proposing defrosting device

In previous study, we proposed an innovative defrosting method using jet impingement to the surface of the cooling tubes[3)]. Figure 1 shows the schematic diagram of the precooled turbojet engine system with the defrosting device. This defrosting device consists of the jet nozzle, valve and high pressure gas feed line. In this system high pressure gas is provided from the downstream of the compressor. This defrosting system needs only few, small components and do not need much mass increase. In the previous study we confirmed the validity of the defrosting method under the condition in which the flow speed is low(1.0 m/s) and the surface temperature of the cooling tubes is 83 K. In this study the fundamental experiment on the defrosting method is performed at various surface temperatures of the cooling tubes. We reveal the effects of the surface temperature of the cooling tubes on the effectiveness of the defrosting method.

Experimental setup

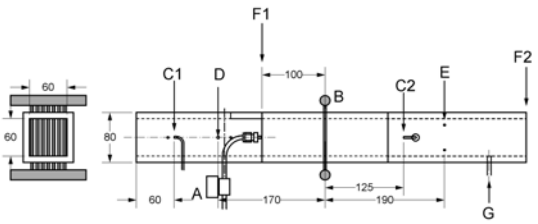
Figure 2 shows the experimental apparatus which we use in this study. The apparatus is composed of a air conditioner (A), duct with a honeycomb section (B), jet supply system and test section. The honeycomb section arranges the air flow straight. A hot wire anemomeer and thermocouple are placed in the inlet. The wall of the test section is made of acrylic resin and whose cross section is 60×60 mm square. In the downstream of the heat exchanger there are two thermocouples. The distances from lower wall to the thermocouples are 10 mm and 50 mm, respectively. The diameters of the thermocouples are 0.25 mm. Two total pressure measurement ports are located at the upstream and downstream of the heat exchanger. These ports are used for the measurement of the pressure loss of the heat exchanger.

The jet supply system is composed of a valve, nozzle, gas feed line and gas nitrogen cylinder. The high pressure nitrogen is provided from the cylinder to the valve. When the valve opens, the jet is ejected from the nozzle. The pressure of the nitrogen is 0.6 MPa at the inlet of the valve. As the nozzle, we used the 1/4-1/8” reducing union made by Swagelok Company. The shape of this union is like a Converging-Diverging nozzle (Fig. 3). The diameter of the throat is 2.3 mm and that of the exit is 5.5 mm. However, the flow does not choke at the throat of the nozzle because the minimum flow path of the valve is



(b) schematic diagram

(b) Picture of the nozzle and the heat exchanger



A: nozzle and valve B: heat exchanger
C1 and C2: pressure measurement port 1 and 2
D: flow speed measurement point
E: thermocouples
F1: nozzle exit and partition
F2: partition G: inlet of purge gas
(c) test section

Fig. 2 Experimental apparatus

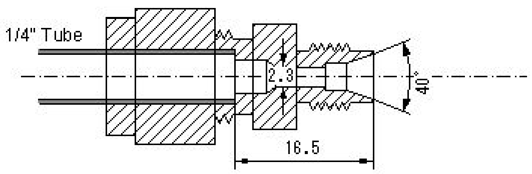


Fig.3 cross section of the nozzle

1.5 mm in diameter. Therefore, the flow chokes at the valve. The nozzle exit is located 100 mm upstream of the heat exchanger. The jet is ejected at the center of the cross section. The direction of the jet is parallel to the flow path. Figure 4 indicates the velocity distribution of the jet measured by a pitot tube. The pitot tube is located at 100 mm from the nozzle exit. This measurement was conducted without the duct and heat exchanger. The maximum speed of the jet is 35.8±0.8 m/s.

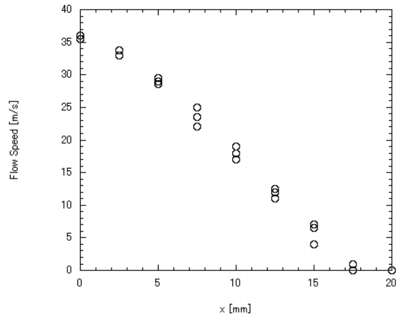
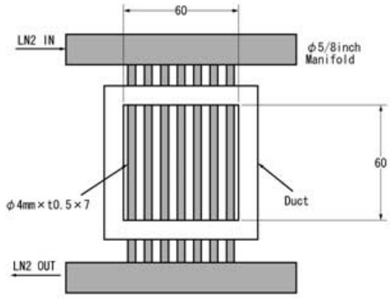
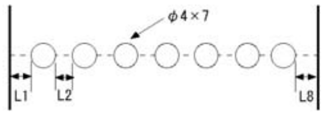


Fig.4 Flow speed distribution of the jet



a) Overview



b) Distance between tubes

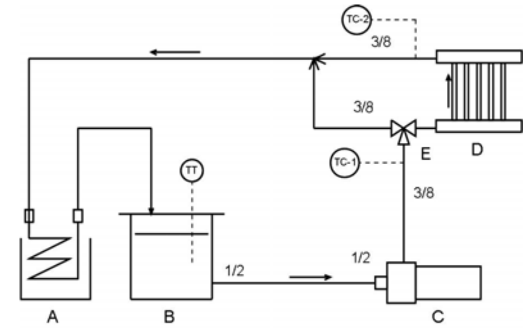
Fig.5 Heat exchanger

Table 1 Test condition

Flow speed	1.0 ± 0.1 m/s
Flow temperature	296 ± 1.0 K
Flow humidity	59 ± 3 %
Total pressure of the jet	0.6 MPa
Surface temp. of the cooling tubes	83, 220, 250 K

Figure 5 shows the heat exchanger which we use in this experiment. The heat exchanger consists of the manifolds, which are the 5/8 inch tubes, and seven cooling tubes whose diameters are 4 mm. All of these tubes are made of stainless steel. The distances between the cooling tubes are 4.6 mm (L2 in Fig. 5) and the distances from the tube to the side wall are 2.3 mm (L1 and L8 in Fig. 5). The flow speed is set to 1.0 m/s before the cooling starts. After the test starts, frost starts to build up on the cooling tubes of the heat exchanger. The frost causes the pressure loss of the heat exchanger. Therefore, the flow speed starts to decrease after the test starts.

In this study we use two kinds of coolant, which are liquid nitrogen and the liquid named Novec. Novec is a kind of hydro-fluoro-ether provided by 3M Company. When we use this coolant, we use the coolant circulation system shown in Fig. 6. In this system the coolant is cooled with the heat exchanger



A: heat exchanger(coolant/liquid nitrogen)
B: coolant tank C: magnet pump
D: heat exchanger (coolant/air)
E: three position valve

Fig. 6 Coolant circulation system

upstream of the tank(A in Fig. 6). The heat exchanger exchanges the heat between the coolant and liquid nitrogen. The lower limit of the coolant temperature produced by this system is about 200 K. In this study we use this system when the objective coolant temperature is 220 and 250 K. On the other hand, when the objective temperature is 83 K we use liquid nitrogen as the coolant. In this case, the liquid nitrogen is provided directly to the heat exchanger designated by D in Fig. 6.

The test procedure is as follows.

(1) Partition plates, which separate the area around the heat exchanger, are inserted at upstream and downstream of the heat exchanger.
(2) Dry nitrogen gas is injected in the area separated by the plates.
(3) Cooling is started by providing the coolant or liquid nitrogen to the heat exchanger.
(4) In five minutes, the coolant temperature of the cooling tubes becomes steady.
(5) The injection of the nitrogen gas is stopped and we remove the partition plates. Then the test starts.

Results

Accuracy of temperature control Figure 7 shows the coolant temperature measured before and after the heat exchanger. In the case of this figure the objective temperatures are 250 and 220 K. In the case of 250 K, the maximum temperature is 251 K and minimum temperature is 248 K throughout the 400-second test. The temperature difference between the inlet and outlet is about 1 K. On the other hand, in the case of 220 K the maximum temperature is 222 K and minimum temperature is 216 K. The temperature difference between the inlet and outlet is larger than that of 250 K, which is about 2-3 K. In the case of 83 K the coolant temperature is very stable. The temperature is 82-84 K and the temperature difference between the inlet and outlet is within 1 K.

Flow characteristics without jet defrosting First we show the results without the jet defrosting. Figure 8 shows the flow speed profiles when the coolant temperature is 250, 220 and 83 K. In each case the flow speed decreases with time proceeding. This is because of the pressure loss caused by frost formation.

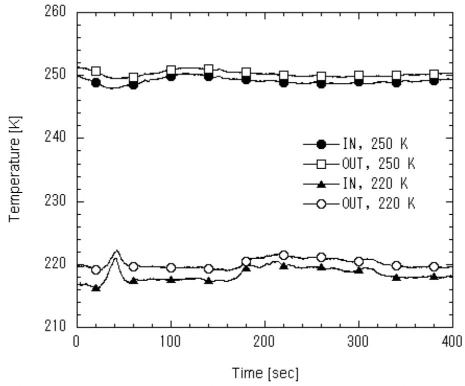


Fig.7 Coolant temperature

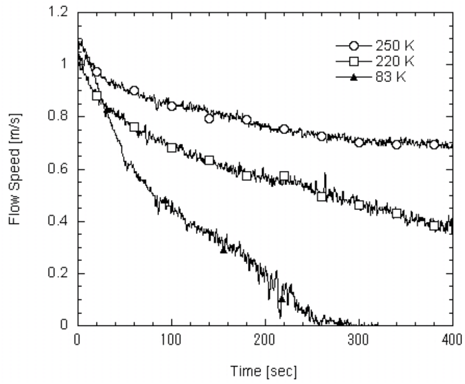


Fig.8 Flow speed

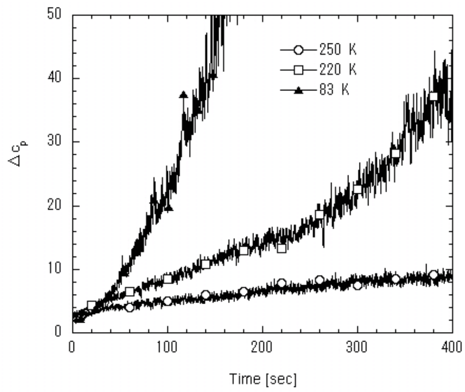


Fig.9 Pressure loss coefficient

In the case of 250 K, the flow speed decreases to 0.65 m/s in 400 second. In the case of 220 K, the flow speed decrease is faster than that of 250 K. In the case of 83 K, the flow speed decrease is much faster. As a result, the flow speed becomes zero at 250 sec.

Figure 9 shows the effect of the coolant temperature on the pressure loss coefficient Δc_p. The pressure loss coefficient is defined as follows.

$$\Delta c_p = \frac{\left(p_{0in} - p_{0out}\right)}{1/2\rho_\infty u_\infty^2} \qquad (1)$$

In the equation (1) p_{0in} and p_{0out} is the measured total pressure before and after the heat exchanger. $1/2\rho_\infty u_\infty^2$ is the dynamic pressure upstream of the heat exchanger. In spite of the decrease in the flow speed, the pressure loss coefficient increases in Fig. 9. This increase is caused by the frost formation on the cooling tubes.

By Fig. 8 and 9 we found that the pressure loss increase is much higher when the coolant temperature becomes lower. However, previous studies said that the mass flux of water vapor becomes lower when the surface temperature becomes lower[4,5]. Therefore, it seems that the frost on the lower temperature tubes is less dense.

Flow characteristics with jet defrosting Figure 10 shows the frost scattering by jet impingement. In this case the coolant temperature is 83 K. We used the jet at 50 second after the test started. The duration of the jet is 0.1 second. We could observe that the frost blew off by naked eye. In the right figure, there remains a thin frost on the tubes even after the jet impingement. But this frost layer is thin enough not to affect the amount of heat transferred and the pressure loss. Figure 11 shows the recovery of the flow speed due to the impingement of the jet. In this case we used the jet periodically, once per 50 second. The flow speed almost recovers to the condition of the test start. After 300 seconds the flow speed does not become zero. The defrosting method using jet impingement is clearly valid in this condition. Figure 12 indicates the recovery of the heat transfer rate by the jet impingement. The heat transfer rate without jet defrosting is also shown in Fig. 12. The definition of the heat transfer rate is as follows.

$$Q = \rho_\infty u_\infty A c_p (T_{in} - T_{out}) \qquad (1)$$

We can see the profiles of the heat transfer rate are similar to that of the flow speed (Fig.11). Figure 13 shows Δc_p with and without jet defrosting. When we do not use the jet defrosting method, Δc_p increases monotonously. On the other hand, when we use the jet we can see the drop of Δc_p every 50 seconds. This is second evidence to indicate that the jet defrosting method is valid in this condition.

Figure 14 shows the profiles of the flow speed with and without the jet defrosting method when the coolant temperature is 220 K. In this case, the frost scattering could be observed, but the amount of the scattering frost is small. We also observed that many frost remains on the cooling tubes even just after the jet impingement. This results in the small recovery of the flow speed in Fig.14. Figure 15 shows Δc_p with and without the jet defrosting. We can see small improvement in Δc_p, but the recovery is smaller than

Fig. 10 Frost scattering by jet impingement. Left: before jet impingement, Right: after jet impingement

that at the coolant temperature of 83 K (Fig.13). As regards the heat transfer rate, we could not obtain the data which have enough accuracy. This is because, when the coolant temperature is relatively high, the

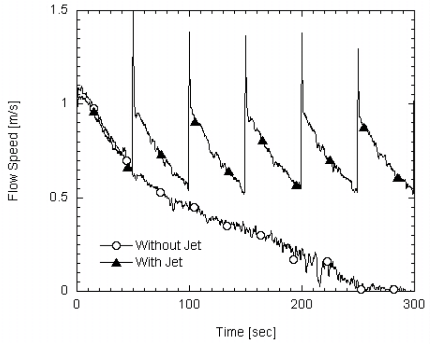


Fig.11 Flow speed, the coolant temperature is 83 K.

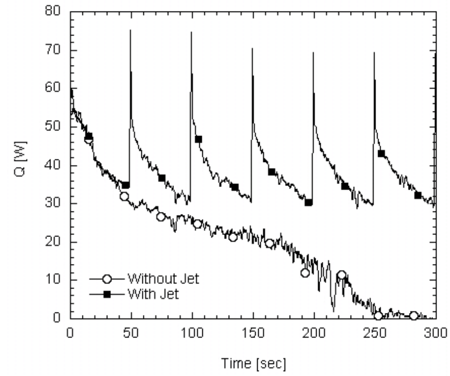


Fig.12 The amount of heat transferred, the coolant temperature is 83 K.

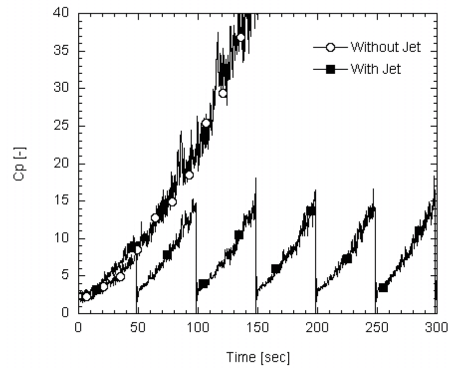


Fig.13 Pressure loss coefficient, the coolant temperature is 83 K.

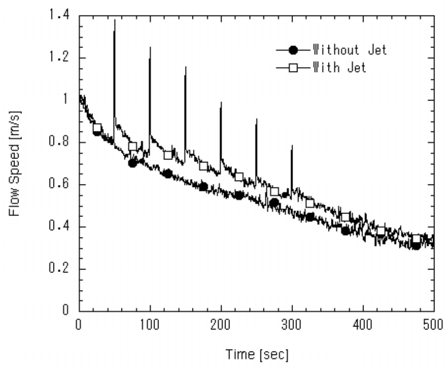


Fig.14 Flow speed, the coolant temperature is 220 K.

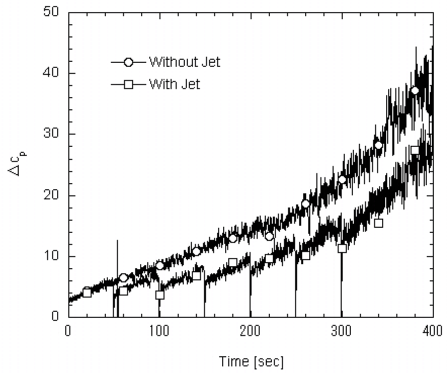


Fig.15 Pressure loss coefficient, the coolant temperature is 83 K.

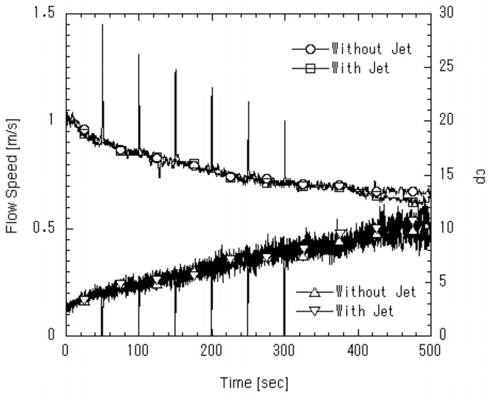


Fig.16 Flow speed and pressure loss coefficient, the coolant temperature is 250 K.

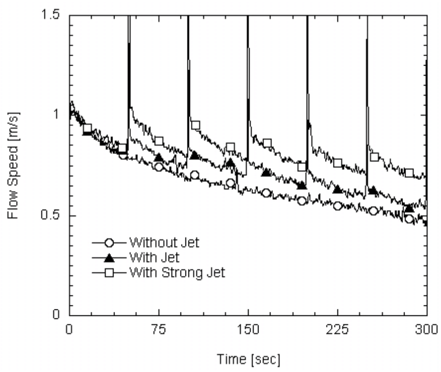


Fig.17 Flow speed with strong jet defrosting

temperature difference between before and after the heat exchanger is small. However, the trend of the heat transfer rate seems to be similar to that of the flow speed as we show in Fig. 11 and 12.

Figure 16 shows the flow speed and Δc_p profiles at the coolant temperature of 250 K. In this case no difference is observed in flow speed and Δc_p profiles. This results indicate that the jet defrosting method is not valid in this condition.

From Fig.11-16, we can see the tendency that, when the coolant temperature increases the jet defrosting method becomes less effective in removing the frost. We think this fact is caused by the difference of the frost firmness. When the coolant temperature is relatively high, the frost surface temperature becomes above melting point. In this case, the liquid water generates on the frost surface and this water makes the frost become firm.

Figure 17 shows the flow speed profiles when we use a very strong jet. In this case the coolant temperature is 220 K. In the experiment until here the small electric valve which has the minimum cross section corresponding to the 1.5 mm diameter circle. This strong jet is made by changing the valve to a large electric valve. The minimum cross section of this valve corresponds to the circle whose diameter is 3.0 mm. This is larger than the diameter of the nozzle throat. In this case the flow does not choke at the valve. Therefore, the mass flow rate and the jet speed increase. By using the strong jet we can see the improvement in the flow speed recovery in Fig. 17. This fact shows that there is possibility to improve the jet defrosting method.

Conclusion

Fundamental experiments with single row heat exchanger were conducted for the purpose of validating new defrosting method by using jet impingement. The coolant temperature were varied from 83 to 250 K. At the test in which we did not use the jet defrosting method, we found the difference in the frost growth speed between the various coolant temperatures results. At the test in which we used the jet defrosting method, the difference in the effectiveness of jet defrosting was observed between the various coolant temperatures. At higher coolant temperature, the frost becomes harder to be blown off. However, the possibility to improve the jet defrosting by increasing the jet velocity was found.

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