Proceedings of Fifth International Conference on **Enhanced, Compact and Ultra-Compact Heat Exchangers: Science, Engineering and Technology**, Eds. R.K. Shah, M. Ishizuka, T.M. Rudy, and V.V. Wadekar, Engineering Conferences International, Hoboken, NJ, USA, September 2005.

CHE2005 – 32

STUDY ON COMPACT HEAT EXCHANGER FOR VEHICULAR GAS TURBINE ENGINE

S. Akama, Y. Himeji, A. Minami, and T. Yoshikawa

4th Research Center, Japan Defense Agency, Technical Research and Development Institute
2-9-54 Fuchinobe, Sagamihara, Kanagawa, JAPAN; sengenan@jda-trdi.go.jp

ABSTRACT

Gas turbine engine is used for combat vehicular propulsion such as a main battle tank. Minimizing volume of engine system and decreasing specific fuel consumption are strongly required for improvement of tank mobility.

Minimizing volume of heat exchanger is an effective approach for the improvement of tank mobility, because the volume of the heat exchanger normally occupies large part in a recuperated vehicular gas turbine engine. However the heat exchanger has to resist higher turbine inlet temperature to increase the engine power and to decrease the specific fuel consumption

In this study, a compact heat exchanger, in which Hastelloy-X was used as a material of offset fins of the plate-fin heat exchanger, was designed and assembled with high heat transfer surface area density about 1750m^2/m^3. The new compact heat exchanger was designed to resist high turbine inlet temperature up to 1673 K. Preliminary performance test results shows that further improvement of the compact heat exchanger would be possible from a point of some margins in pressure loss rates of gas flow paths.

INTRODUCTION

Firepower, mobility and survivability are very important factors for main battle tanks. The performances of the engine system deeply affect the tank mobility. For example, minimizing volume of engine system under the same power enables us to design a smaller chassis of the tank. As a result of the smaller volume of engine system, the tank would be able to move more quickly. On the other hand, decreasing specific fuel consumption enlarges the cruising range under the same fuel quantity. Consequently minimizing volume of engine system and decreasing specific fuel consumption are strongly required for improvement of tank mobility.

Gas turbine engine is one of the options of engine system for combat vehicles such as a main battle tank, since the striking advantages are the high power produced in such a small package, quietness, clean exhaust, multiple fuel and quick engine start capabilities (down to 219K).(1)(2) The heat exchanger is used to reduce specific fuel consumption in the gas turbine engine installed for vehicular propulsion.(3) However, in current recuperated vehicular gas turbine engine, the heat exchanger is occupied over 1/3 of the engine system volume. Therefore, it is an effective approach to minimize the volume of heat exchanger by increasing heat transfer surface area density. The compact heat exchanger is expected to be a major contribution in the improvement of the tank mobility.

At the same time of minimizing the heat exchanger volume, rising turbine inlet temperature (TIT) is necessary to achieve both of increase of the engine power and decrease of the fuel consumption so that the tank can move more quickly and have more long cruising range. Turbine inlet temperature 1673K class vehicular gas turbine engine have been studied.(4)(5) However rising turbine inlet temperature requires more heat resistant material of the heat exchanger due to increase the maximum gas temperature of the heat exchanger.

The present paper describes the results of the investigation on our newly designed compact heat exchanger for vehicular gas turbine engine, which has high heat transfer surface area density and capability to resist high inlet gas temperature.

DESIGN AND MAKING UP THE HEAT EXCHANGER

Design of the Heat Exchanger

In this study, the heat exchanger for the TIT 1673K class and maximum power 1100kW class gas turbine engine was considered.

The performance of this heat exchanger was considered at following design conditions:

(1) Maximum inlet gas temperature is 1023K and maximum inlet air temperature is 573K. These

values are obtained from the cycle analysis at maximum power for the TIT 1673K class gas turbine engine.

(2) Temperature efficiency is 75%. This value is the same as that for the heat exchanger of the gas turbine engine, which was already installed for vehicular propulsion.[6]

(3) Maximum pressure loss rate of the gas and the air are 5.3% and 0.9%. These values are almost equal to the value for the heat exchanger of the gas turbine engine, which was already installed for vehicular propulsion .[6]

The air introduced to the vehicular gas turbine engine (total air flow) is divided into the primary air flow and the secondary air flow at the compressor. The primary air flow, which is heated through the heat exchanger, is burned in the combustion chamber and produces high temperature and high pressure exhaust gas flow. The secondary air flow, which cools the high temperature parts (turbine blade, turbine disk, bearing and so on), is mixed with the exhaust gas flow. Then the mixed gas is introduced to the heat exchanger and heats up the primary air flow. In this study, for 1100kW class vehicular gas turbine engine, the secondary air flow is assumed as 5% of the total air flow ((Primary air flow rate) / (Total air flow rate) = 0.95). Therefore, the design conditions for the mass flow rates are as follows:

(4) Primary air flow rate is 3.36kg/s,
Secondary air flow rate is 0.18kg/s, and
Exhaust gas flow rate is 3.54kg/s.

Also the heat exchanger in this study is 1/6 blocks of the heat exchanger for 1100kW class vehicular gas turbine engine.

(5) The mass flow rate of the gas supplied to the heat exchanger is 0.59kg/s.

(6) The mass flow rate of the air supplied to the heat exchanger is 0.56kg/s.

Table 1 shows the performances and the operation limits of this heat exchanger.

Table 1 Performances and Operation Limits

Maximum Inlet Temperature	Gas	1023K
	Air	573K
Temperature Efficiency		75%
Pressure Loss Rate	Gas	5.3%
	Air	0.9%
Maximum Mass Flow Rate	Gas	0.59kg/s
	Air	0.56kg/s
Maximum Inlet Air Pressure		1.19MPa

Structure of the Heat Exchanger

Figure 1 shows the structure of the plate-fin heat exchanger in this study. This heat exchanger consists of main heat exchanging zone, in which over 85% heat transfer are performed, and headers which supply and discharge the air.

Offset fin was selected at the main heat exchanging zone, in which heat transfer was performed with counter flow in order to increase heat transfer coefficient.

This heat exchanger was shaped symmetrically as shown in figure 1, and the top and the bottom layers were plugged to reduce thermal stress.

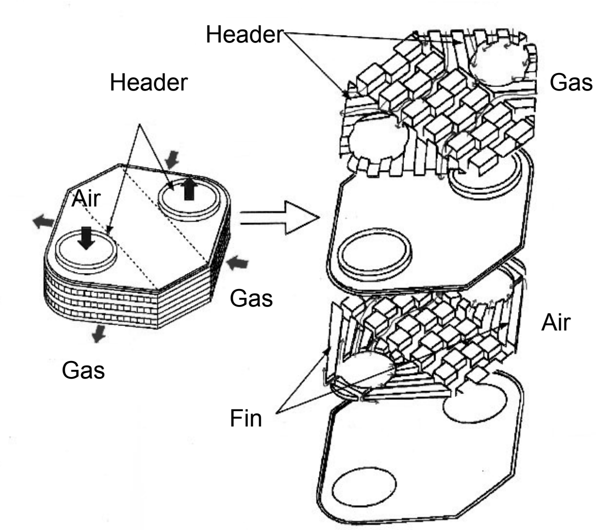


Figure 1 Structure of the Heat Exchanger

Figure 2 shows the cross section of main heat exchanging zone. As shown in this figure, gas flow path and air flow path are piled alternately, and they are isolated by separation plate.

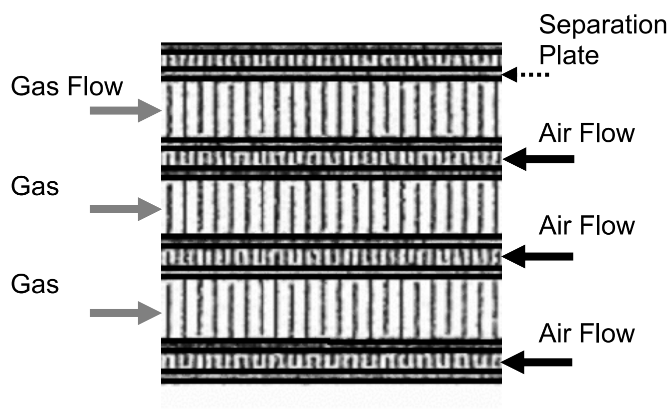


Figure 2 Cross Section of Main Heat Exchanging Zone

Hastelloy-X, heat resistant nickel based alloy, is selected as a material for this heat exchanger, because it endures up to 1023K (the inlet gas temperature of the heat exchanger).

Dimensions of the Offset Fin

To reduce the volume of the heat exchanger, it is important to increase the heat transfer surface area density. Therefore, it is desirable for the length, width and height of the offset fin as shown in figure 3 to be fine as much as possible. On the other hand, the pressure loss increases for too fine dimensions of the offset fin.

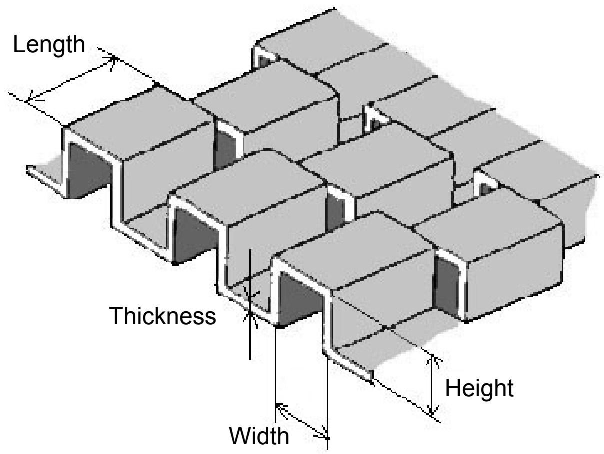


Figure 3 Offset Fin

The inlet gas pressure was about 0.1MPa and the inlet gas velocity was about 34m/s. The pressure loss of the heat exchanger will be increase, when the fin size becomes too small. The relation between the fin size and the volume of the heat exchanger was investigated under the performances and the operation limits shown in Table 1. The dimensions of the gas side fin were selected as 4.5mm height and 2.2mm width to minimize the volume of this heat exchanger.

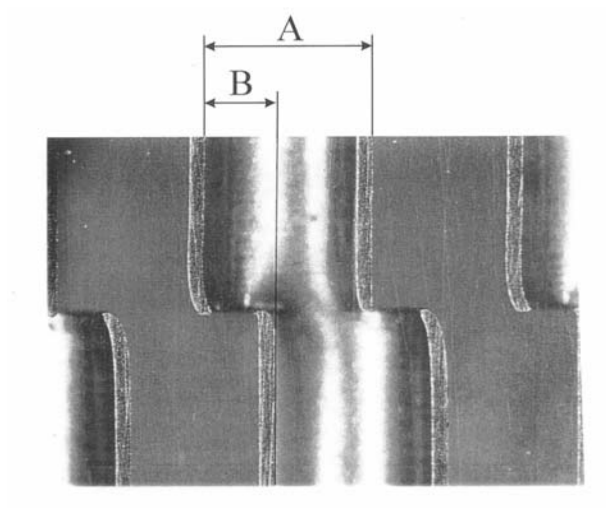
When the width and the height of the air side fin are 1mm, the pressure loss rate is considered to be lower than the value in Table 1 at the conditions of the inlet air pressure about 1.2MPa and the inlet air velocity about 9.5m/s. Lower limitation of the offset fin dimensions has to be examined, because it is difficult to form Hastelloy–X plate under 1mm fin size. The minimum dimensions of the fin with 0.15mm thickness Hastelloy-X plate were examined by mechanical forming.

It is also important to reduce the aberration of the offset, the burr, the crack at the corner and so on, because they cause the decrease in the temperature efficiency and the increase in the pressure losses. Table 2 summarizes the factors which adversely affect the performance of the heat exchanger.

Figure 4 illustrates the definition of the offset rate, offset rate = B/A as shown in this figure. Offset rate 0.5 is the best value. When the offset rate (B/A) is deviated from 0.5, the velocities of air at left and right side of fin become different. At the case shown in figure 4, the offset rate is 0.47.

Table 2 Factors which adversely affecting the Performance of the Heat Exchanger

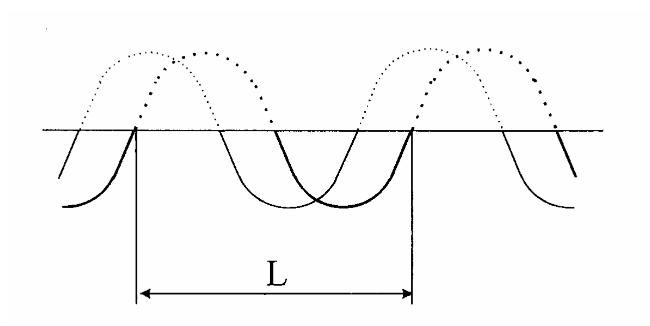
No.	Factors	Influenced Performance
1	Aberration of the offset	Temperature Efficiency
2	Existence of the Burr	Pressure Loss Rate
3	Reduction of the Thickness	Toughness, Temperature efficiency
4	Accuracy of the Fin Height	Temperature Efficiency
5	Fin Pitch	Pressure Loss Rate, Temperature Efficiency
6	Offset Length	Pressure Loss Rate, Temperature Efficiency
7	Distortion of the Fin Plate	Temperature Efficiency
8	Crack	Toughness



Offset Rate = B/A

Figure 4 Definition of the Offset Rate

Figure 5 shows the fin pitch which is twice of width in Figure 3.



Fin Pitch = L = 2 *Width

Figure 5 Fin Pitch

The burr is shown as circled in Figure 6. Figure 6 shows the best case to form the fin dimensions (1.5mm width and 1.5mm height fin) for this heat exchanger. In this case, reduction of the flow area was 2.9%, compared to the designed value. The burr as shown in this figure does not influence the pressure loss rate as mentioned after.

From the results of these examinations, the dimensions of the fin for air flow path were decided as 1.5mm width and height 6.0mm length.

The dimensions of the fins are summarized as Table 3. The heat transfer surface area density at main heat exchanging area with these fin dimensions was about 1750 m^2/m^3.

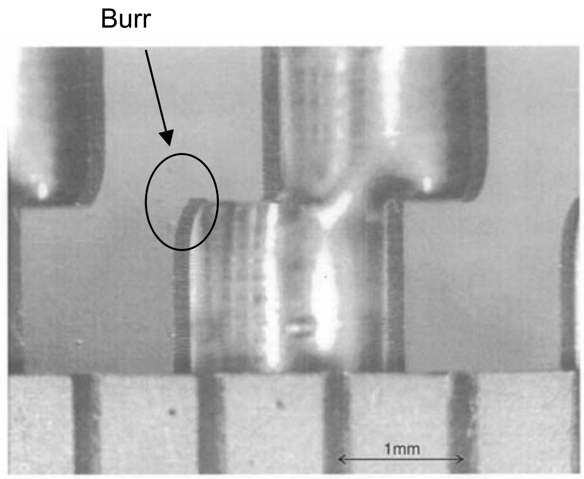


Figure 6 Cross Section of the Fin

Table 3 Dimensions of the Offset Fin

		Dimension	
		Air Side	Gas Side
Thickness	t	0.15	0.20
Height	H	1.50	4.50
Pitch	W	1.50	2.20
Offset Length	X	6.00	15.0

Assembly of the Heat Exchanger

Fins and separating plate which separates air flow path and gas flow path were brazed. Figure 7 shows the cross section of the joined zone. It was found that the brazing metal fully penetrated and the reduction of the heat transfer area and the plug of air flow path were not existed.

Twenty eight pairs of gas and air layers shown as Figure 2 were piled and assembled into the heat exchanger. Figure 8 shows an appearance of the assembled heat exchanger and its dimensions.

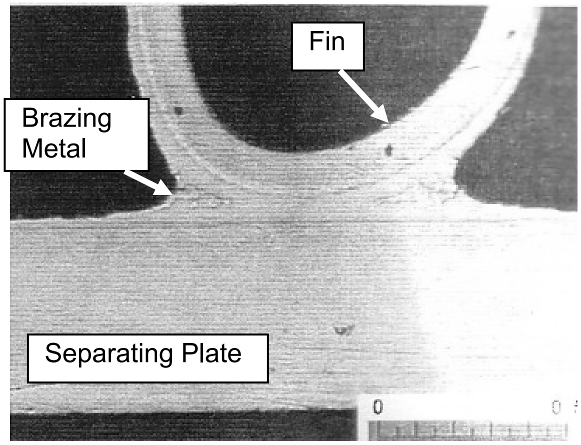
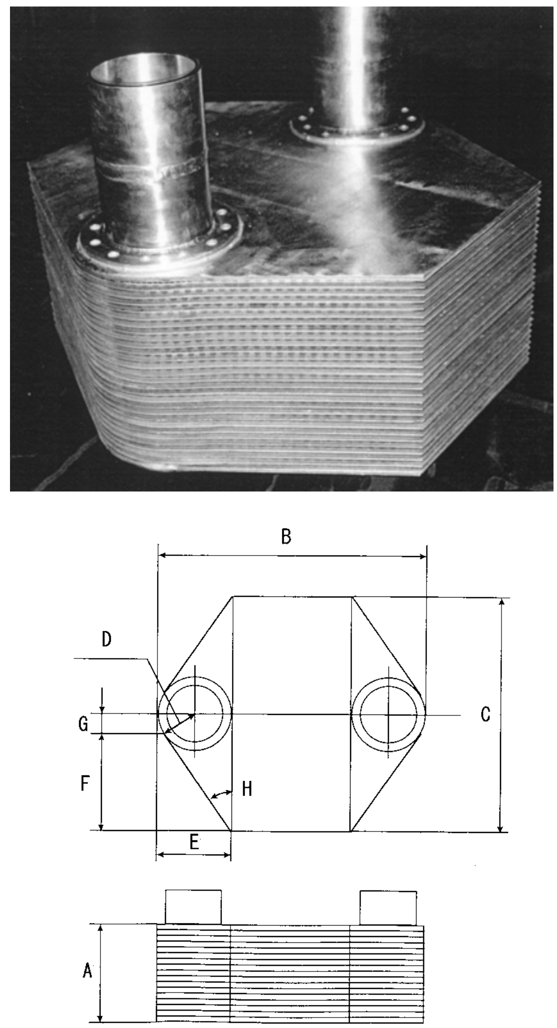


Figure 7 Joined Zone of the Fin



A	215mm	E	142mm
B	515mm	F	206mm
C	503mm	G	46mm
D	86mm	H	32°

Figure 8 Assembled Heat Exchanger

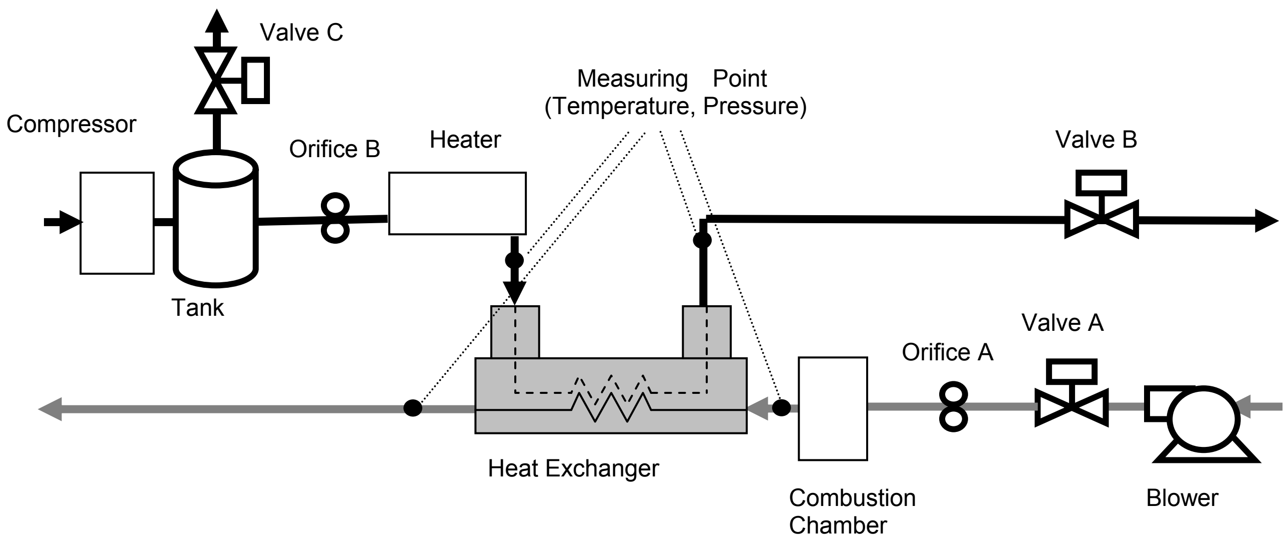


Figure 9 Experimental Apparatus

PRELIMINARY PERFORMCANCE TEST RESULTS AND DISCUSSION

Preliminary performance test for the heat exchanger was conducted to check the performances with the experimental apparatus shown in Figure 9. Exhaust gas side air was introduced to combustion chamber through the valve A, which regulated flow rate of the air, and orifice A, which measured flow rate of the air. This flow rate simulates to the exhaust gas flow rate of the vehicular gas turbine engine. In the combustion chamber, kerosene was burned and combustion gas was generated. The temperature of the combustion gas, which is same as the exhaust gas temperature of the vehicular gas turbine engine, was supplied to the heat exchanger. The maximum gas temperature was controlled at 1023K to correspond to the inlet gas temperature of the vehicular gas turbine engine at maximum power.

Compressed air stocked in the regulated tank was supplied to the heat exchanger through the orifice B, which measured flow rate of the compressed air, and the electric heater. The temperature of the air is same as the heat exchanger inlet air temperature of the vehicular gas turbine engine. Heat exchanged compressed air was introduced to the valve B, which regulated inlet air pressure. This air pressure is same as the heat exchanger inlet air pressure of the vehicular gas turbine engine. The flow rate of the compressed air was regulated with valve C, which was set on the regulated tank, and it corresponds to the heat exchanger inlet air flow rate of the vehicular gas turbine engine. The flow rate of the compressed air was measured with orifice B.

The ratio between the air flow rate and the gas flow rate was kept as 0.95 as mentioned before.

The temperatures and the pressures were measured at the locations as shown in Figure 9. The temperature efficiency (η) and the pressure loss rates (ΔP) were calculated as follows.

$$\eta = \frac{Taout - Tain}{Tgin - Tain}$$

$$\Delta P = \frac{Pin - Pout}{Pin}$$

T: temperature, P: Pressure
a: air side, g: gas side
in: inlet, out: outlet

The test results acquired by the preliminary performance test are shown in Table 4.

Table 4 Results of the Preliminary Performance Test

		Designed Value	Performance Test Result
Inlet Temperature (K)	Gas	1023	1029
	Air	573	572.1
Flow Rate (kg/s)	Gas	0.59	0.586
	Air	0.56	0.558
Temperature Efficiency (%)		75	75.2
Pressure Loss Rate (%)	Gas	5.3	2.7
	Air	0.9	0.4

It was shown that the air side pressure loss rate was 0.4% and gas side pressure loss rate was 2.7%. These values were about 1/2 of the designed value. As mentioned before, it was difficult to form the fin dimension under

1.5mm width and height , so the dimensions of the fin for air flow path were decided as 1.5mm width and height 6mm length.

Heat transfer surface area does not change under constant aspect ratio of a fin, when the dimensions of a fin change. If the dimensions of the fin are diminished at a condition that the aspect ratio of the fin and the temperature efficiency are fixed, the heat transfer surface area density, the pressure loss, and the velocity of the gas will increase. For the gas flow path of this heat exchanger, the dimensions of the fin were calculated to increase gas side pressure loss rate to 5.3% (designed value) with Wieting's formula(7) under the constant aspect ratio of the fin (4.5/2.2). It was found that height and width of the fin are 3.5mm and 1.75mm and these dimensions were able to be formed. Therefore, the volume of this heat exchanger can be further decreased about to 17%.

CONCLUSIONS

(1) Compact heat exchanger was made with high heat transfer surface area density at main heat exchanging area about 1750 m^2/m^3, and the maximum inlet gas temperature of this heat exchanger is 1023K using Hastelloy-X, heat resistant nickel based alloy.

(2) It was shown that the temperature efficiency was 75%, air side pressure loss rate was 0.4% and gas side pressure loss rate was 2.7% by the preliminary test of this heat exchanger. They were about 1/2 of the designed value.

(3) The height of offset fin at gas flow paths would be able to make smaller, because there was some margin for pressure loss rates of gas flow paths. Therefore, the volume of this heat exchanger would be able to presume to decrease about 17% still more.

ACKOWLEDGEMENT

The authors wish to thank Ishikawajima-Harima Heavy Industries Co., Ltd. and JAMCO Corporation for their contribution to the making this heat exchanger.

REFERENCES

(1) V. Kadambi, et al., "Primary Surface Heat Exchanger for a Ground Vehicle Gas Turbine", SAE Paper, 920148, 1992.

(2) C. Banthin, et al., "Battle Tanks of the Future - A Need for Turbine Power", ASME Paper, 88-GT-43, 1988.

(3) R. J. Duffy, et al., "Turbine Propulsion for Heavy Armored Vehicles", AIAA Paper, AIAA-87-1911, 1987.

(4) W. Brockett, et al., "LV100 AIPS Technology - For Future Army Propulsion", ASME Paper, 92-GT-391, 1992.

(5) N. Nakazawa, et al., "Status of the Automotive Ceramic Gas turbine Development Program - Seven Years Progress-", ASME Paper, 97-GT-383, 1997.

(6) H. F. Jen, "Primary Surface Recuperator for Vehicular Gas turbine", SAE Paper, 871590, 1987.

(7) A. R. Wieting, "Empirical Correlations for Heat Transfer and Flow Friction Characteristics of Rectangular Offset-Fin Plate-Fin Heat Exchangers", Journal of Heat Transfer, TRANS. ASME, Aug. 1975, pp488-490.