E3S Web of Conferences **313**, 05001 (2021) https://doi.org/10.1051/e3sconf/202131305001
19° International Stirling Engine Conference

A Study of Mesh Sheets of 3-kW Stirling Engine

Takeshi Enomoto[1], Atsushi Matsuguchi[2], Noboru Kagawa[3]
[1] National Defense Academy
1-10-20 Hashirimizu, Yokosuka, 239-8686 JAPAN, em59023@nda.ac.jp
[2] National Defense Academy
1-10-20 Hashirimizu, Yokosuka, 239-8686 JAPAN, matsu@nda.ac.jp
[3] National Defense Academy
1-10-20 Hashirimizu, Yokosuka, 239-8686 JAPAN, kagawa@nda.ac.jp

Keywords: Stirling engine, Regenerator, Mesh sheet.

Abstract. In recent years, the interest in low-pollution and high-efficiency heat engines has been increasing due to the growing awareness of environmental protection, and power generation at relatively low temperatures, such as use of exhaust heat and sunlight, has been attracting attention. Compared with other heat engines, Stirling engine is very important because it can be driven by any heat source at low temperatures, such as exhaust heat, and it does not emit exhaust gas. In order to realize a more efficient Stirling engine, it is essential to design a heat exchange system that is suitable for each component.

Performance measurement and analysis on a new mesh regenerator material at low temperature difference using a 2-piston alpha-type 3-kW Stirling engine, NS03T are carried out. Mesh sheets developed for high performance Stirling engines can be designed with CAD and CAM technologies by etching process. For this study, M5 and M7 mesh sheets which are thin sheets of stainless steel with square holes in a grid arrangement, are used. With nitrogen and helium as the working fluid, the engine performance is measured by changing the charge pressure, heating temperature, and engine speed to clarify the flow resistance and heat transfer characteristics of the M5 and M7.

NOMENCLATURES

d	:	distance, depth
d_m	:	diameter of wire
l	:	opening
n	:	engine speed
P	:	pressure
p	:	pitch
Q	:	quantity of heat
t	:	thickness
W	:	power
w	:	width
V	:	volume
β	:	opening area ratio
Δ	:	difference
η	:	efficiency
σ	:	specific surface area
ϕ	:	porosity
ν	:	kinematic viscosity coefficient
N	:	number of stacked sheets
ρ	:	density
T	:	temperature
c_p	:	constant pressure specific heat
λ	:	thermal conductivity of working fluid
w_i	:	instantaneous mass flow rate

Subscripts

C	:	cooler
c	:	compression
cc	:	compression cylinder
e	:	expansion
ec	:	expansion cylinder
eff	:	effective
g	:	groove
ind	:	indicated
mean	:	mean
out	:	output
p	:	pressure
total	:	total
rloss	:	regenerator loss
x	:	direction in x
y	:	direction in y

1. INTRODUCTION

With an aid of heat-recovery mechanism between two isochoric processes of a Stirling cycle, the cycle efficiency, so-called indicated efficiency becomes higher and improves the total thermal efficiency. The heat-recovery mechanism, so called regenerator, plays a very important role in Stirling cycle machines. If a regenerator of a Stirling engine works ideally, required heat input supplied at a heater and/or an expansion cylinder of the engine and rejected heat at a cooler and/or a compression cylinder become minimum. To develop the Stirling engine, it is essential to design and develop a suitable regenerator for the engine.

There are many kinds of proposed regenerator matrix materials, e.g., wire, foil, wire screen (gauze), metal felt, foamed metal. For high-performance engines, generally, stacked wires screens woven from fine wire have been used by the reason of their high heat capacity, uniform, homogeneous, and simple fabrication. On the other hand, its disadvantage is the sealing of the periphery. Also, the limited type of woven sheets is trouble for developers. The geometry and dimensions of marketed wire screens are usually standardized, and specially ordered one is very expensive. Obviously, it would be better to use a matrix material, which has not only the flexibility to design its geometry and dimensions, but also good characteristics better than wire screens.

In this study, we evaluated the newly developed M5 Mesh sheet and M7 Mesh sheet. It was made of thin metal sheet. M5 is a square hole arranged in a grid pattern; M7 is M5 with an additional groove in the square hole. Regenerator of the 3-kW Stirling engine, NS03T was equipped with mesh sheets as a matrix.

The engine with one of the mesh sheets was operated under the condition of low temperature difference of 500°C to 550°C and working fluid of helium or nitrogen. From the measuring data, the regenerator losses and pressures losses of the regenerator are calculated. Based on the results, the characteristics of the mesh sheet matrix are discussed.

2. SPECIFICATIONS OF NS03T

Table 1 shows the design parameters of the NS03T engine, which was one of the engines developed from 1982 to 1988 in Toshiba[1]. The heater was changed to an electric heater from the combustion type. Figure 1 shows a schematic view of the engine used for this study. Table 2 shows the NS03T engine specifications.

Table 1. Design parameters of the 3-kW engine

Items	Parameter
Mean pressure	3.0 MPa
Max heater temp	1023.15 K
Cooling system	Water cooling
Engine speed	500 – 1500 rpm
Max. output power	> 3 kW
Max. thermal efficiency	32 %

Table 2. Engine specifications

Items	Data
1. Engine	
Type	Two piston
Swept volume	
Expansion	169 cm^3
Compression	169 cm^3
Volume Phase angle	90 degrees
2. Piston	
Bore x Stroke	
Expansion	82 mm x 32 mm
Compression	82 mm x 32 mm
3. Regenerator	
Type	Canned
Dead volume	150 cm^3
Matrix Outer diameter x Length	70 mm x 54 mm

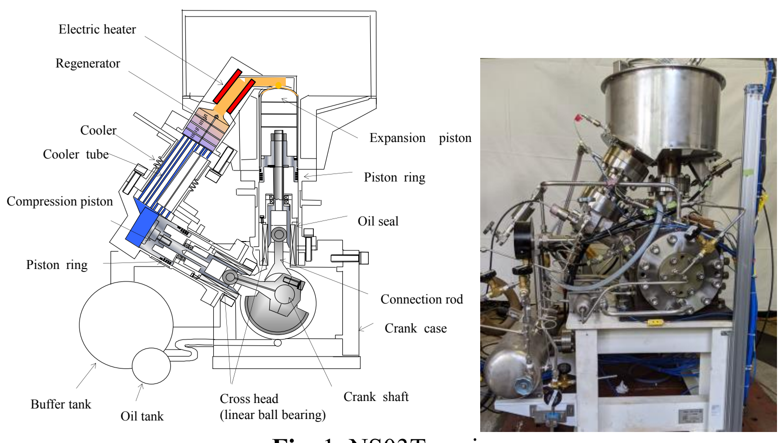

Fig. 1. NS03T engine

3. SPECIFICATIONS OF MESH SHEET

Figures 2, 3 and 4 show schematic views of the mesh sheets. As shown in the figures, the holes and grooves are arranged on each thin disk made of stainless steel 304. M4 is only made of nickel. Stacking M4 only was firmly bonded by a metallic surface modification after the engine operations. To avoid the bonding M4 is used in alternating layers with M3. Small square holes and shallow grooves are etched on one of the circular surfaces. The disk has a flat edge around the etched area. The precisely cut edge reduces the side leakage of the working gas. For the stainless steel rod of the matrix holder with the wheel-shaped rims, each sheet has a hole, 3 mm in diameter in its center.

These holes, grooves, and shape are made by an advanced etching technology. Table 3 shows the geometric parameters of the evaluated matrixes in this paper. As shown in Table 3, these three sheets have the same pitch between the holes, but other dimensions have changed; opening width, thickness, and depth of the grooves.

In comparison, M5 is a staggered-hole mesh sheet (M1, M2, M3 and M4) with a reduced dead volume and an increased aperture ratio to reduce the flow resistance. M7 is shaped with

https://doi.org/10.1051/e3sconf/202131305001

steps in the stranded portion of M5 to reduce the contact area between the sheets and to reduce heat conduction loss.

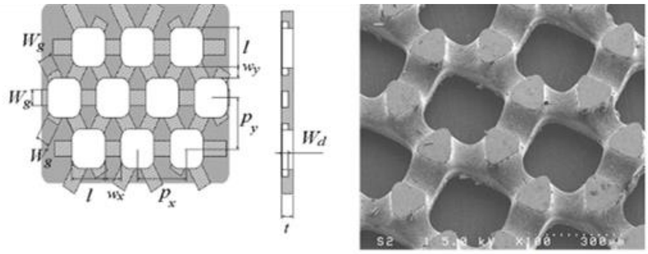

Fig. 2. Mesh sheet M1, M2, M3 and M4

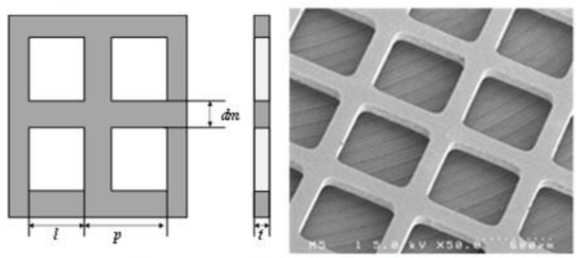

Fig. 3. Mesh sheet M5

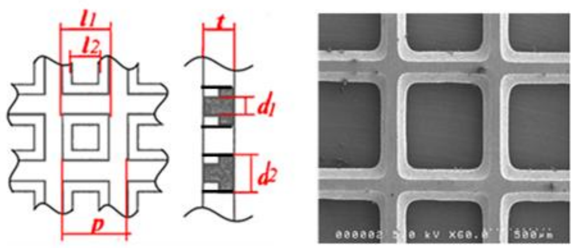

Fig. 4. Mesh sheet M7

Table 3. Geometric parameters of matrix

Dimension	#200	M1 Mesh sheet	M2 Mesh sheet	M3 Mesh sheet	M4 Mesh sheet	M5 Mesh sheet	M7 Mesh sheet
Opening l (mm)	0.066	0.242	0.280	0.300	0.300	0.650	l_1 : 0.680 l_2 :0.580
Diameter d_m (mm)	0.061	---	---	---	---	0.150	d_1 :0.100 d_2 :0.200
Width of frame (mm)	---	w_x : 0.199 w_y : 0.140	w_x : 0.161 w_y : 0.102	w_x : 0.141 w_y : 0.082	w_x : 0.141 w_y : 0.082	--- ---	--- ---
Pitch p (mm)	0.127	p_x : 0.441 p_y : 0.382	p_x : 0.441 p_y : 0.382	p_x : 0.441 p_y : 0.382	p_x : 0.441 p_y : 0.382	0.800	0.800
Groove w_g x d_g (mm)	---	0.120 x 0.060	.120 x 0.060	0.150 x 0.072	140 x 0.060	---	---
Thickness t (mm)	0.122	0.100	0.100	0.120	0.100	0.100	0.100
Open area ratio β	0.270	0.315	0.433	0.487	0. 502	0.660	0.738
Porosity ϕ	0.582	0.543	0.606	0.667	0.668	0.660	0.738
Specific surface area σ (mm^{-1})	21.502	21.058	17.990	14.487	16.141	10.859	13.084

4. ENGINE PERFORMANCE

The engine with the new matrix was driven and its performance was measured. Thermocouples, pressure transducers, and crank-angle pickup sensors were attached to the engine. The output power was measured by a dynamometer. A data logger and a digitizer converted the analog signals received from the transducers and sensors to digital signals. The data are acquired by a personal computer (PC). Calculations of the engine performance, a display of the results and the engine operating conditions, and acquisition and saving of the data are automatically carried out by a software written with a graphical programming language. Table 4 describes the definitions of the powers, heats, losses, and efficiencies. ΔW_p means difference between a calculated W_{ind} in the case of no pressure losses and the actual W_{ind}. Effective heat input, and Q_{rloss} are derived from heat fluxes in the engine[1]. The typical operating conditions are arranged in Table 5.

Table 4. Definitions of powers and efficiencies

Items	Equations
1.Power	
Expansion work (power)	$W_e = n\oint P_e dV_e$
Compression work (power)	$W_c = n\oint P_c dV_c$
Indicated work (power)	$W_{ind} = W_e - W_c$
Pressure loss	$\Delta W_p = \left(\oint P_e dV_c + \oint P_c dV_e - W_{ind}\right)/2$
2.Quantity of heat	
Cooling heat in cooler (quantity)	Q_c
Cooling heat in comp. cyl. water jacket (quantity)	Q_{cc}
Regenerator loss	$Q_{rloss} = Q_{cc} - W_c$
Effective heat input	$Q_{eff} = Q_{rloss} + W_e$
3.Efficiency	
Indicated efficiency	$\eta_{ind} = W_{ind} / Q_{eff}$
4.Friction loss	
Friction coefficient	$f_l = \dfrac{\Delta P}{\frac{1}{2}\rho u^2 N}$
Pressure loss	$\Delta P = \dfrac{\Delta W_p \cdot \rho}{w_i}$
Reynolds number	$Re_l = \dfrac{l \cdot u_l}{\nu}$
5.Heat transfer	
Number of transfer units	$N_{tu} = \dfrac{2wc_p(T_{rh} - T_{rl})}{Q_{rloss}} - 2$
Average heat transfer coefficient	$\alpha = \dfrac{wc_p N_{tu}}{S}$
Nusselt number	$Nu_d = \dfrac{d_m \alpha}{\lambda}$
Reynolds number	$Re_d = \dfrac{l \cdot u_d}{\nu}$

Table 5. Operating conditions

Items	Parameter
Working fluid	Helium, Nitrogen
Mean pressure	2.0, 2.5 MPa
Engine speed	500 – 1500 rpm
Heater temp.	773 - 823K
Compression space temp.	283 – 293 K (water cooling)

Power

The indicated power, W_{ind} figures are shown in Figures 5, 6 and 7. In the figures, the data series are fitted with curves to clarify the behaviors. Nitrogen shows high W_{ind} at 700 rpm wiht M5 , 800 rpm with M3+M4 and M7. Above 900 rpm, helium shows the higher W_{ind}. Maximum W_{ind} was 948 W at with M3+M4, which was 51 W bigger than M5 and 4 W bigger than M7.

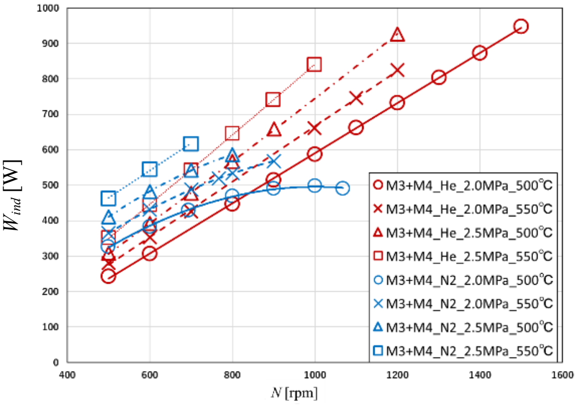

Fig. 5. Indicated power with M3+M4 Mesh sheet

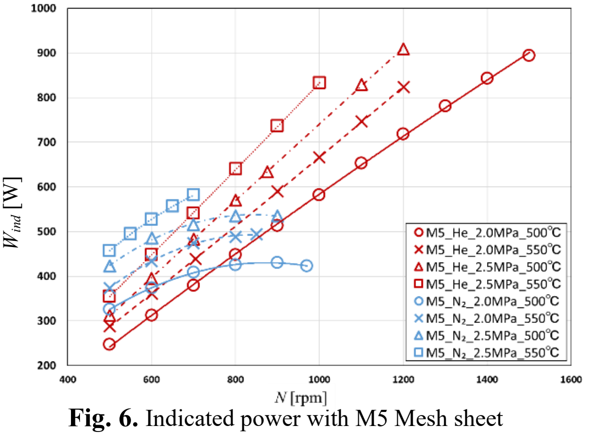

Fig. 6. Indicated power with M5 Mesh sheet

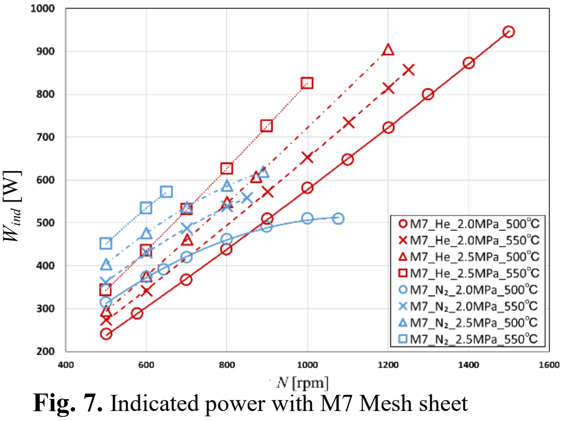

Fig. 7. Indicated power with M7 Mesh sheet

Efficiencies

The Indicated efficiency, η_{ind} are shown in Figures 8, 9 and 10 for M3+M4, M5 and M7. The η_{ind} of nitrogen is bigger than that of helium when the speed is below 700 rpm. η_{ind} of nitrogen decreases above 700 rpm and is high under the operation using helium. The maximum η_{ind} was 31% with M3+M4, 30% with M5, and 31% with M7.

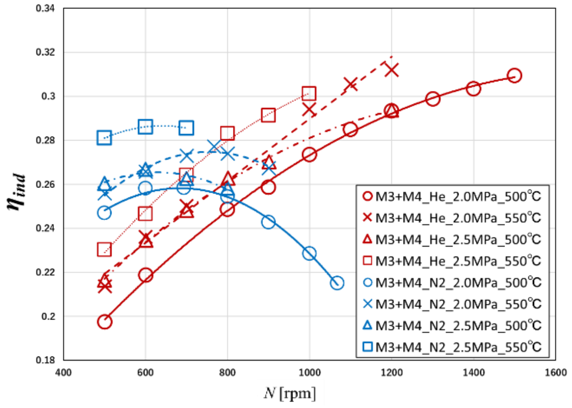

Fig. 8. Indicated efficiency in M3+M4 Mesh sheet

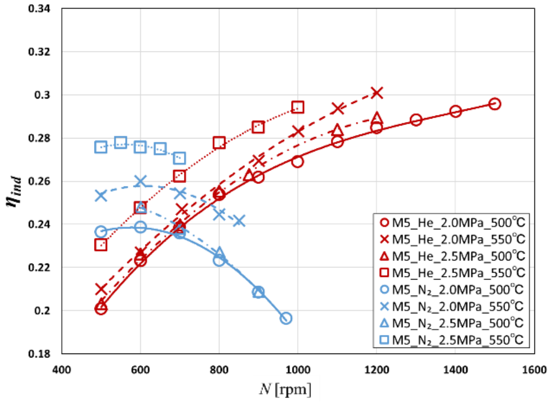

Fig. 9. Indicated efficiency in M5 Mesh sheet

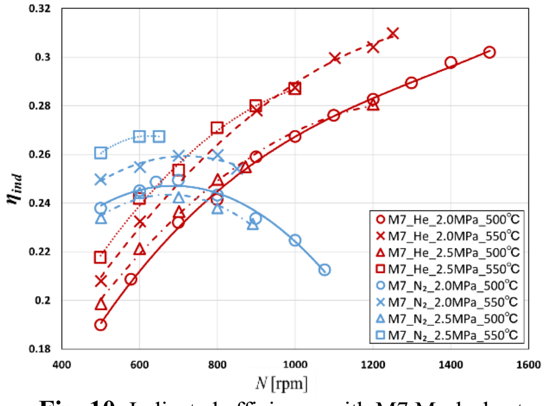

Fig. 10. Indicated efficiency with M7 Mesh sheet

Pressure loss

The pressure loss, $\varDelta W_p$ is shown in Figures 11, 12 and 13. This loss is caused by a frictional resistance in the heat exchangers, including the heater, the cooler, and the regenerator. The loss reduces W_{ind} directly. For both M5 and M7, nitrogen has a higher pressure drop than helium, and the pressure drop tends to be higher at 500 °C and 2.5 MPa. It seems that high pressure and low temperature increase the density of the working fluid and increase the fluid friction in the matrix. The $\varDelta W_p$ of M7 tends to decrease compared to M3+M4 and M5.

M3+M4 and M5 were bigger than M7 by 34 W and 80 W for nitrogen and 60 W and 105 W for helium.

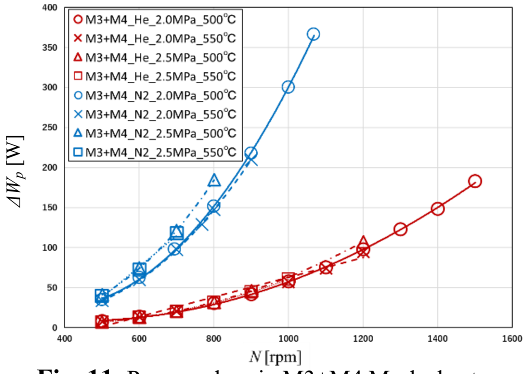

Fig. 11. Pressure loss in M3+M4 Mesh sheet

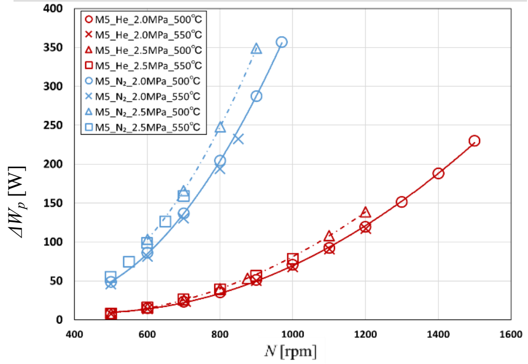

Fig. 12. Pressure loss in M5 Mesh sheet

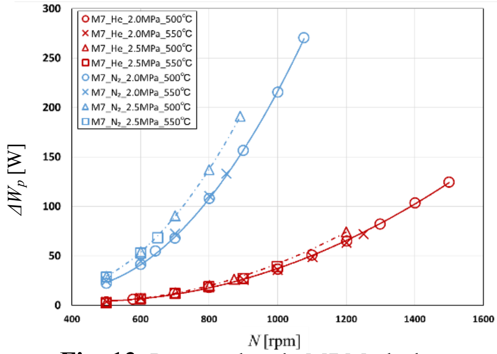

Fig. 13. Pressure loss in M7 Mesh sheet

Regenerator loss

The Regenerator loss, Q_{rloss} is show in Figures 14, 15 and 16. Q_{rloss}, which includes the reheat and thermal conduction losses, are calculated from the quantities of the rejected heat from the cooler, the cooling heat at the water jacket of the compression cylinder, and the compression power. Therefore, the derived data have some uncertainty and scatter in the figures. Helium has a high thermal conductivity, has a lower Q_{rloss} than nitrogen. M7 with nitrogen was 400 W larger than M5 with nitrogen.

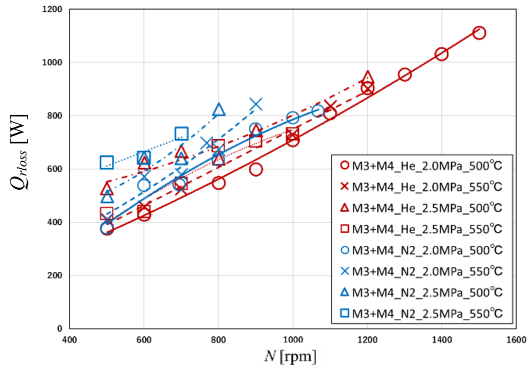

Fig. 14. Regenerator losses in M3+M4 Mesh sheet

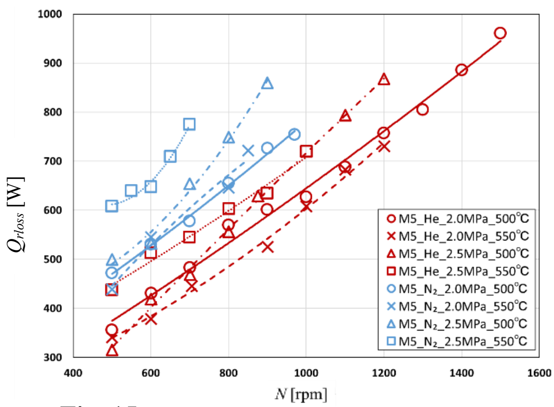

Fig. 15. Regenerator losses in M5 Mesh sheet

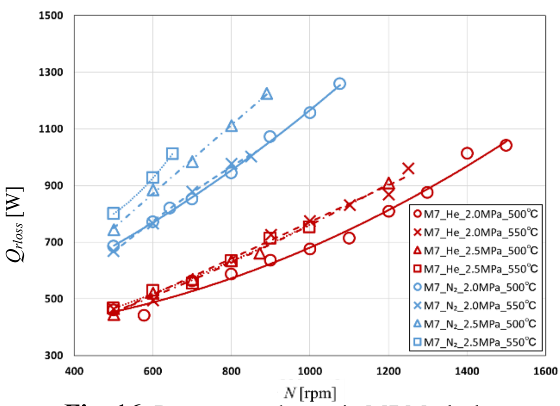

Fig. 16. Regenerator losses in M7 Mesh sheet

https://doi.org/10.1051/e3sconf/202131305001

Friction coefficient

The friction coefficient, f is show in Figure 17.#200, M1, and M2 are obtained from the results of previous research by Kitahama[2]. The pressure loss, ΔP caused by the flow loss in the regenerator is converted to a friction factor, f and evaluated as a function of the Reynolds number, *Re*. The experimental equation of Tanaka[3] for unsteady reciprocating flow is also shown.

M7 is low friction coefficient and shows characteristics similar to #200 and M3+M4. The M5 is a higher friction coefficient than the M7.

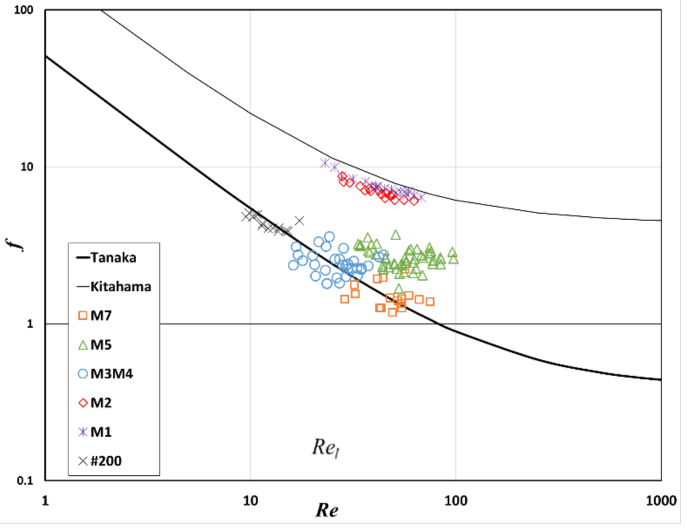

Fig. 17. Friction coefficient with *Re*

Nusselt number

The Nusselt number, *Nu* is show in Figure 18. The heat transfer characteristics of the regenerator are evaluated by the relationship between *Nu* and *Re*. M7 tends to be the same as #200 and M1. M5 had a higher Nusselt number than M7.

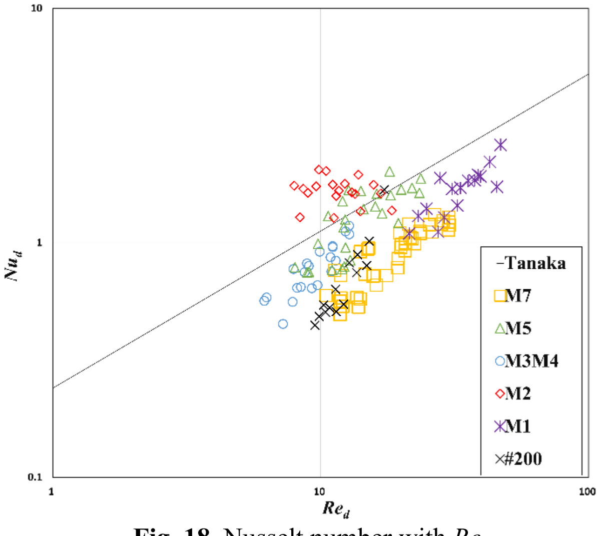

Fig. 18. Nusselt number with *Re*

5. CONCLUSIONS

In this paper, the performances of the new mesh sheet for regenerator were presented. Three types of the mesh sheet were manufactured, and were installed in the NS03T. The engine performances with the mesh sheets were measured.

Maximum W_{ind} of M3+M4, M5 and M7 are 948 W, 909W and 944 W. And Maximum η_{ind} of M3+M4, M5 and M7 are 0.312, 0.301 and 0.310. W_{ind} of M7 is 6% higher than M5 and η_{ind} of M7 is 3% higher than M5. This is due to M7 has a smaller diameter *dm* than M5.

Q_{rloss} of M7 with nitrogen was 400 W larger than M5 with nitrogen. This is because the *dm* of M7 was smaller M5. Smaller *dm* decrease heat regeneration.

Nitrogen has higher values of both W_{ind} and η_{ind} than Helium below 700 rpm. However, Pressure loss is considered to be larger due to the size of nitrogen atom, Pressure loss is considered to be larger. It becomes clear that a suitable mesh sheet with a smaller *f* likes M3+M4 and M7 is required to increase the engine power especially for changing nitrogen.

ACKNOWLEDGEMENTS

The authors acknowledge Mr. Kennichi Tamura of Japan Defense Foundation for Mutual Aid.

REFERENCES

1. Kagawa, N., Sakamoto, M., Nagatomo, S., Komakine, T., Hisoka, S., Sakuma, T., Arai, Y., and Okuda, M., *Development of a 3 kW Stirling Engine for a Residential Heat Pump System*, Proc. 4th Int. Conference Stirling Engines, Japan Society of Mechanical Engineers, Tokyo, pp. 1-6.(1988)
2. Kitahama, D., Takizawa, H., Tsuruno, S., Sawahata, Y., Matsuguchi, A., Kagawa, N., *Performance of New Matrix for Stirling Engine Regenerator*, The 6th symposium on Stirling Cycle, Japan Society of Mechanical Engineers, Tsukuba, pp. 70-74, in Japan.
3. Tanaka, M., Yamasita, I., Chisaka, F,. *Flow and Heat Transfer Characteristics of Stirling Engine Regenerator in Oscillating Flow*, Transactions of the Japan Society of Mechanical Engineers. **Series B**., pp. 2478-2485(1989)