NASA TECHNICAL MEMORANDUM

NASA TM-77448

Revised

FLOW LOSSES OF REGENERATOR MATRIX (CASE OF PACKED WIRE GAUZES)

K. Hamaguchi, S. Takahashi, H. Miyabe

Translation of "Saiseiki Matrix no Ryudo Sonshitsu," Nippon Kikai Gakkai Ronbunshu, Series B, Vol. 48, No. 435, 1982, pp. 2207-16

NATIONAL AERONAUTICS AND SPACE ADMINSISTRATION
WASHINGTON D.C. 20546 JUNE 1984

STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-77448		

4. Title and Subtitle	5. Report Date
FLOW LOSSES OF REGENERATOR MATRIX (CASE OF PACKED WIRE GAUZES)	JUNE 1984
	6. Performing Organization Code

7. Author(s)	8. Performing Organization Report No.
K. Hamaguchi, S. Takahashi, H. Miyabe	
	10. Work Unit No.

9. Performing Organization Name and Address	11. Contract or Grant No.
SCITRAN Box 5456 Santa Barbara, CA 93108	NASw- 3542
	13. Type of Report and Period Covered
	Translation

12. Sponsoring Agency Name and Address	14. Sponsoring Agency Code
National Aeronautics and Space Administration Washington, D.C. 20546	

15. Supplementary Notes

Translation of "Saiseiki Matrix no Ryudo Sonshitsu," Nippon Kikai Gakkai Ronbunshu, Series B, Vol. 48, No. 435, 1982, pp. 2207-2216.

16. Abstract

Several wire gauzes (10-300 mesh) were packed as the regenerator matrix to study the flow losses in the steady and unsteady states. Empirical equations were derived for the friction coeff.

17. Key Words (Selected by Author(s))	18. Distribution Statement
	Unclassified and Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	28	

FLOW LOSS OF REGENERATOR MATRIX (CASE OF PACKED WIRE GAUZES)*

Kazuhiro Hamaguchi, Shintaro Takahashi, Hideya Miyabe**

#/2207

1. Preface

Gauze has been used since old times for the purpose of fast amplification of channel cross-sections, homogenization of flow velocity and shake-out of pulsating flow by taking advantage of its resistance. Therefore, studies of flow loss have been mostly of one piece of gauze [1,2].

However, recently a gauze which has great strong points of specific surface (heating surface per unit volume) has been paid attention to. This began to be used in a Sterling engine as the matrix material of the regenerator (heat regenerator) which switches low temperature fluid with high temperature fluid in a short time by laminating several gauzes [3-7]. However, studies of flow loss of several laminated gauzes have not been done often and we have only been informed of the results of tests of steady flow by Tong [8] and Mori [9] and of unsteady flow by Yamada [10].

Tong and others understood the flow loss of gauze as a shear force and evaluated from 5 mesh to 60 mesh gauze using the coefficient of friction. Byt this is difficult to use as the coefficient of friction varies, depending on the mesh of each gauze; and also the method of calculating the hydraulic equivalent diameter is not clear. Also, Mori and others recognized that the flow loss in gauze is the pressure drop per single gauze. They evaluated from 10 mesh

* This report was presented at the 23rd Lecture Meeting of the Hokkaido Branch on Sept. 13, 1981. Receipt of the report was April 27, 1981.

** Regular member, Engineering Dept. at Meiji University (Higashimita 1-1-1, Tamaku, Kawasaki city 214).

Numbers in margin indicate pagination of foreign text.

to 50 mesh gauze, evaluating by the coefficient of friction. Although the usage of this is arranged by an easy equation (the same as in the former example), the mesh number of the sample gauze is small. Also, since the coefficient of friction was obtained over a narrow range, there is some question about applying it to a Sterling engine for which a large mesh number is used. Also, Yamada, et al., laminated 500 gauzes of mesh 200, which are often used for Sterling engines [7], and evaluated the coefficient of friction by understanding flow loss in gauze as a shear force in the unsteady flow experiment, but this is difficult to apply to other meshes.

Because of this, we fabricated matrix materials from several laminated gauzes which have a wide range from 10 mesh to 300 mesh. We studied the flow loss with steady flow experiments and unsteady flow experiments and we found an empirical formula which gives a coefficient of friction that can be easily used to determine flow loss.

2. Symbols and subscripts used

Symbols

b : constant of proportionality m^{-1}

d_m : wire diameter mm

f : coefficient of friction

K : transmittance

l : aperture mm

m : mass kg

n : number of laminated sheets

P : pressure Pa

p : pitch mm

p_r : pitch ratio

R : gas constant J/kg·K

R_e : Reynolds number

T : absolute temperature K

t : time s

u : average flow velocity in matrix m/s

u_o : average flow velocity before matrix m/s

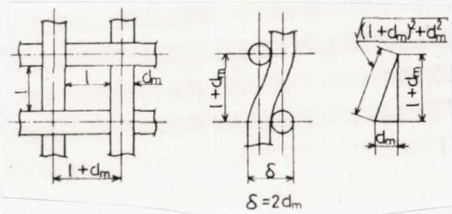


Figure 1. Inspection volume of gauze

V_r : reservoir capacity m^3

β : opening ratio /2208

δ : thickness of one gauze mm

μ : coefficient of viscosity Pa·s

ν : coefficient of kinematic viscosity m^2/s

ρ : density kg/m^3

σ : specific surface mm^2/mm^3

ϕ : free volume

Subscripts

1: entrance of the matrix

2: exit of the matrix

d: wire diameter

l: aperture

t: time

3. Geometric configuration values of sample gauzes

In order to define the configuration values of gauzes, we considered the test volume of one mesh to be as in Figure 1 in this study. Namely, curves were considered as approximately straight lines and the configuration values were defined as follows. The heat surface area of the test volume was found after the polymerized points were subtracted from the total surface area by considering the unavailable heat surface area at element wire polymerization.

(a) pitch: $p = l + d_m$

(b) pitch ratio: $p_r = d_m / p$

(c) opening ratio:

$$\beta = \frac{\text{minimum free channel area}}{\text{total front area}} = \left(\frac{l}{p}\right)^2$$

(d) free volume:

$$\phi = \frac{\text{free channel area}}{\text{total volume}} = 1 - \frac{\pi d_m \sqrt{p^2 + d_m^2}}{4p^2}$$

(e) specific surface:

$$\sigma = \frac{\text{heat area}}{\text{total volume}} = \frac{\text{total surface} - \text{surface area of polymerization points}}{\text{total volume}}$$

$$= \frac{\pi(2\sqrt{p^2 + d_m^2} - d_m)}{2p^2}$$

TABLE 1. Geometrical configuration value of sample gauzes

mesh	wire no.	pitch p mm	wire diameter d_m mm	aperture l mm	pitch ratio p_r	opening ratio β	free volume φ	specific surface σ $\frac{mm^2}{mm^3}$
10	25	2.540	0.508	2.032	0.200	0.640	0.840	1.14
20	32	1.270	0.274	0.996	0.216	0.615	0.827	2.26
40	34	0.635	0.233	0.402	0.367	0.401	0.693	4.36
50	36	0.508	0.193	0.315	0.380	0.385	0.681	5.44
60	36	0.423	0.193	0.230	0.456	0.296	0.606	6.47
	40		0.121	0.302	0.286	0.510	0.766	6.66
80	40	0.317	0.121	0.196	0.382	0.382	0.679	8.72
100	42	0.254	0.101	0.153	0.398	0.363	0.664	10.85
120	44	0.211	0.081	0.130	0.384	0.380	0.677	13.09
150	45	0.169	0.071	0.098	0.420	0.336	0.642	16.26
180	47	0.144	0.050	0.091	0.355	0.417	0.705	19.69
200	47	0.127	0.050	0.077	0.394	0.368	0.668	21.72
250	48	0.101	0.040	0.061	0.396	0.365	0.665	27.30
300	48	0.084	0.040	0.044	0.476	0.274	0.586	32.52

Table 1 shows the configuration values of every weave of gauze of each mesh used in the test of flow loss. The material of each gauze is SUS-27, except for copper in the 40 mesh gauze. In order to distinguish the mesh number, wire number and number of sheets of gauze, the laminated gauzes used in this experiment are described as follows:

(mesh number) - (number of wire) - (number of sheets)

For example, 80-40-20 means a matrix consisting of 20 laminated gauzes of 80 mesh and 40 wires each.

4. Investigation by steady flow experiments

14 kinds of gauze ranging from 10 mesh to 300 mesh were laminated, and the flow loss was studied with steady flow experiments.

4.1 Experimental equipment and methods

The experimental equipment for measuring flow loss for steady flow is shown in Figure 2. Polyvinylchloride pipe of 66.8mm diameter was used, and the matrix was installed in the midpoint of the channel (position M in the figure).

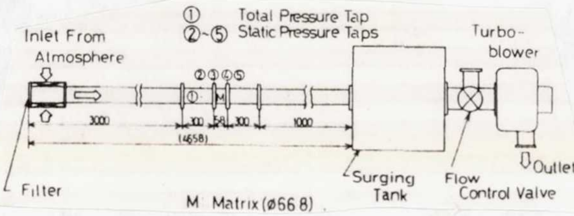


Figure 2. Experimental equipment of steady flow

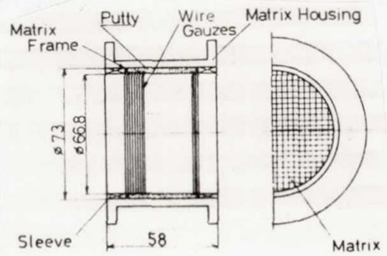


Figure 3. Matrix and its container /2209

Air was drawn in from outside with a turboblower (maximum air capacity 8 m^3/min, maximum wind pressure 5.7 kPa). We inserted a filter-paper-style filter at the air suction entrance to avoid depositing dust on the matrix. Figure 3 shows the matrix and its container. Each sample matrix was laminated after the periphery of the gauzes had been brazed. The portion around the matrix was compacted with heat-resistant putty to make an effective bore diameter of 66.8mm. We inserted them into the matrix container and fixed it on both edges through a sleeve.

The adjustment of flow rate was performed by a valve which was installed between the surge tank and the inlet port of the air blower. The experiment was performed in the range of 0.4 to 10 m/s average flow velocity before the matrix. For the measurement of flow velocity, pitot tubes and Betts type manometers were used at positions 1 and 2 before the matrix; static pressure and total pressure were measured, the flow distribution was found, and the average flow velocity was calculated. To measure the pressure drop ΔP of the matrix, the static pressure difference between positions 3 and 4 10mm before and after the matrix was measured with Betts type manometers. In the cases when pressure drop exceeded 1.96 kPa, a U-shaped tube water column type manometer was used.

4.2 Equations

In this study, the average flow u and the pressure drop ΔP in the matrix were used for the coefficient of friction f, and if the pressure drop per single gauze $\Delta P/n$ is divided by the dynamic pressure at the entrance of the matrix, the following equation is defined.

$$f = \frac{\Delta P}{n} \Big/ \frac{1}{2}\rho u^2 \qquad (1)$$

where flow velocity u is the value of the average flow velocity u_o, before the matrix, divided by the opening ratio β

$$u = u_0/\beta$$

Reynolds' number is considered to use the gauze aperture l or the wire diameter d_m as a hydraulic equivalent diameter. The following equations are defined for the former, for which a subscript l is attached to R_e, and the latter, for which a subscript d is attached to R_e.

$$R_{el} = \frac{lu}{\nu} \qquad (2)$$

$$R_{ed} = \frac{d_m u}{\nu} \qquad (3)$$

Next, we estimate the flow in the matrix and study the relationship between Reynolds number and the coefficient of friction. Since in the interior of laminated gauzes, fluid flows through a curved passage which changes in both direction of flow and cross-section, the force of inertia of the fluid in areas of low fluid velocity is considered to be much smaller than the force of viscosity. Because of this, we ignore this point and apply Darcy flow depending on the flow within the pores [11].

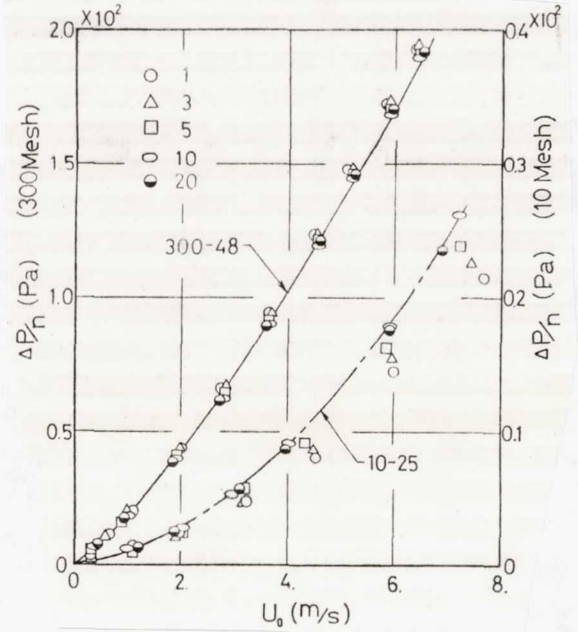


Figure 4. Lamination number and pressure drop

Also, it is considered that, as flow velocity increases, the influence of the force of inertia appears. The flow loss in areas of highest flow velocity described by the following equation which adds the component of the force of inertia to the viscosity force component.

$$\frac{dP}{dx} = -\left(\frac{\mu}{K}\beta u + b\rho u^2\right) \qquad (4)$$

Here, in order to verify the pressure drop $\Delta P/n$ in equation (1), we set

$$-\frac{dP}{dx} = \frac{\Delta P}{\Delta x} = \frac{\Delta P}{2nd_m}$$

If we find the relationship between the coefficient of friction and Reynolds number by using equations (1) to (4), equation (5) will be obtained when the hydraulic equivalent diameter is taken as the aperture l, and equation (6) will be obtained if this hydraulic equivalent diameter is taken as wire diameter d_m.

$$f = \frac{A_l}{R_{el}} + B_l \quad \left(A_l = \frac{4l\beta d_m}{K},\ B_l = 4bd_m\right) \qquad (5)$$

$$f = \frac{A_d}{R_{ed}} + B_d \quad \left(A_d = \frac{4\beta d_m^2}{K},\ B_d = 4bd_m\right) \qquad (6)$$

4.3 Experimental results and discussion

4.3.1 Influence of the number of gauze laminations

In order to study the influence of the gauze lamination number on pressure drop per single gauze, the number of laminations is changed and the relationship between flow velocity and pressure drop is shown in Figure 4.

According to the figure, the case of 10 mesh, which has a large pitch, has a large variance depending on the number of layers of gauze. But, if there are more than 10 layers, the variance will become smaller.

Also, in the case of the 300 mesh gauze which has a small pitch, the variance is generally small. Therefore, it is considered that the size of the number of gauzes does not much influence the pressure drop if the number of laminations is greater than 10. From these results, we will use a lamination number of 20 for the following experiments.

/2210

4.3.2 The influence of space between laminations

In order to study the influence of the space between laminated gauzes on the pressure loss per single gauze, two kinds of matrix were made in which the space between each layer of gauze was 0.4 and 1.0 mm, in the case of 20 laminations of 60 mesh gauze. From these samples, we performed a comparison experiment with a matrix that is closely laminated and obtained the results of Figure 5.

From Figure 5, we understand that there is no change at a space between laminations of 0.4 mm, but at a space between laminations of 1.0 mm as flow velocity increases, some increase in pressure drop occurs. From these results, each gauze was closely laminated.

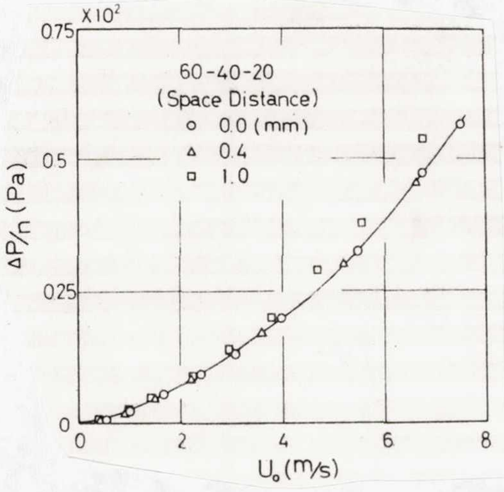


Figure 5. Space between laminations and pressure drop.

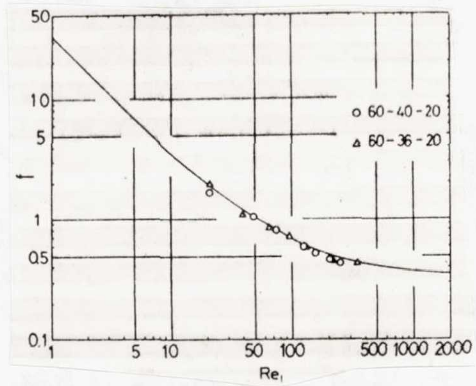


Figure 6. Pitch ratio and coefficient of friction

4.3.3 The influence of pitch ratio

In order to study the relationship between pitch ratio and the coefficient of friction, two kinds of gauze which are wire number 36, 60 mesh (pitch ratio 0.456) and 40 wire number, 60 mesh (pitch ratio 0.286) were laminated with 20 layers and a comparison experiment was performed. Using equations (1) and (2), the results of Figure 6 were obtained.

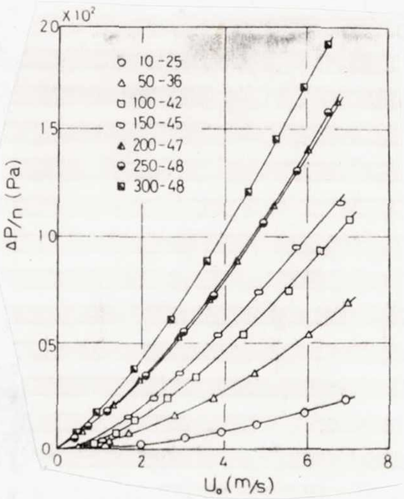


Figure 7. Pressure drop of each mesh

We found from Figure 6 that at the same mesh, a change in pitch ratio does not influence the coefficient of friction. Because of this result, we decided to use only one wire number per mesh in the following experiments.

4.3.4 Pressure drop of each mesh

In order to study the relationship between flow loss and flow velocity in the matrixes mentioned in Section 4.2 and also the appropriateness of equations (5) and (6), we will exhibit the results of the pressure drop of seven kinds of gauze, which are from 10 mesh to 300 mesh, in Figure 7. We realize from Figure 7 that there is a tendency for the pressure drop to be proportional to the flow velocity in areas of low flow velocity. As flow velocity increases, pressure drop is proportional to the square of the flow velocity. We can consider this result to be equivalent to the hypothesis of Section 4.2, where it is said that the influence of the force of inertia for an increase in flow velocity cannot be ignored as the force of inertia is small at a low flow velocity. As a result, we realized that equations (5) and (6), which indicate the relationship between coefficient of friction and Reynolds number found in section 4.3.3, are sufficiently appropriate. Because of this reason, we decided to use the same equation for the experimental values and to find the empirical equation by determining the coefficients A and by using the least squares method.

4.3.5 The relationship between the coefficient of friction and Reynolds number

We obtained the following results from an experiment in which 20 pieces of 12 kinds of gauze, from 10 mesh to 300 mesh, were closely laminated.

(1) The case when aperture l is chosen as the hydraulic equivalent diameter.

Taking the aperture l as the hydraulic equivalent diameter of Reynolds number, each point in Figure 8 exhibits the relationship of /2211
friction coefficient with aperture l.

The continuous line in the figure verifies equation (5) based on the experimental value of each point, and this is the value of the empirical equation obtained from the least squares method. The following is the empirical equation.

$$f = \frac{33.6}{R_{el}} + 0.337 \qquad (4 \leq R_{el} \leq 1\,000) \qquad (7)$$

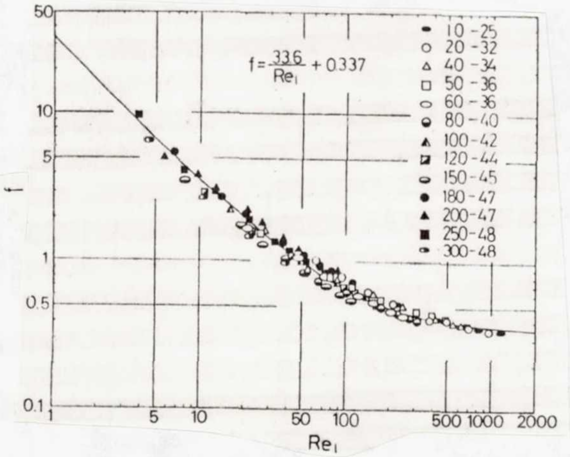


Figure 8. Coefficients of friction for each mesh.

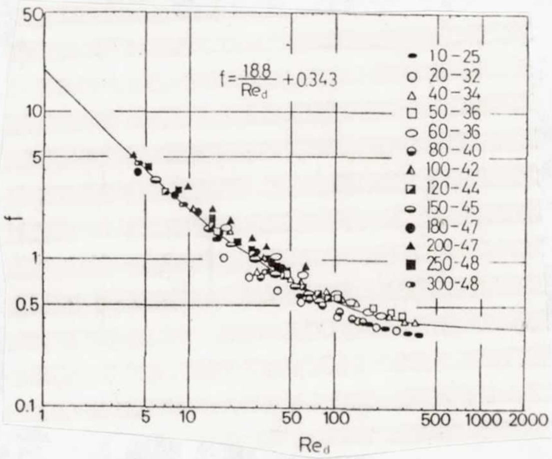


Figure 9. Coefficient of friction of each mesh

(2) The case when wire diameter d_m is chosen as hydraulic equivalent diameter.

Figure 9 exhibits the relationship of the coefficient of friction with wire diameter d_m taken as the hydraulic equivalent diameter of Reynolds number. The continuous line in the figure verifies equation (6) based on the experimental value of each point, and this is the value of the empirical equation obtained by using the least squares method. The following equation shows the empirical equation.

$$f = \frac{18.8}{R_{ed}} + 0.343 \qquad (4 \leq R_{ed} \leq 400) \qquad (8)$$

Comparing Figure 8 with Figure 9, it is understood that, for the variance of each experimental value towards the empirical equation, that of Figure 9 is larger.

This result shows that it is easier when choosing hydraulic equivalent diameter to choose aperture l rather than wire diameter d_m. In the steady flow experiment, the flow in gauze is considered to be a composite of the flows inside a linear tube which has a square cross-section with a side of aperture l length, and a sudden shrinkage and magnification of the cross-section at the inlet and outlet of the cross-section of the tube.

Therefore, it is understood that it is better to describe the coefficient of friction of laminated gauzes under steady flow by using the empirical equation (7) with aperture l chosen as the hydraulic equivalent diameter.

5. Investigation by unsteady flow experiment

Since in a regenerator the actuation fluid pressure always changes with time, the flow loss must be considered as an unsteady condition. We laminated six kinds of several gauzes from 50 mesh to 300 mesh, performed unsteady flow experiments and studied flow loss.

5.1 Experimental equipment and method

Figure 10 shows the experimental equipment for measuring flow loss under unsteady flow.

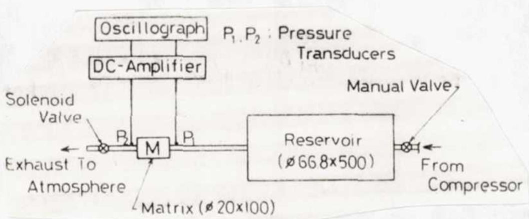


Figure 10. Experimental equipment for unsteady flow.

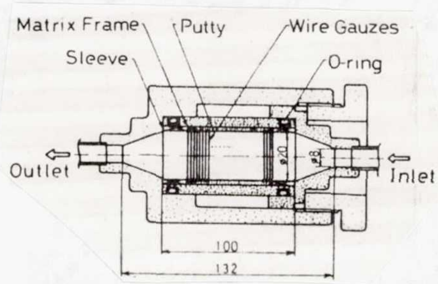


Figure 11. Matrix and its container

We fill the reservoir (ϕ 66.8x500) with air (0.05-1.0 MPa) under constant pressure at room temperature, which was compressed beforehand by a compressor. If we open the solenoid-operated valve located behind the matrix, then immediately the air in the reservoir passes through the matrix (ϕ 20x100) via the channel (copper tubing ϕ 8) and discharges in the air. During this expansion of the filled air, the change in pressure (P_1, P_2) of both sides of the matrix is recorded on an electromagnetic oscillograph through a direct current amplifier, by using a small scale semiconductor pressure converter. /2212

Figure 11 shows a matrix of several laminated gauzes and its container.

The laminated gauzes for each sample matrix were soldered and hammer hardened around the peripheral portion with head resistant putty, and the effective bore was made 20 mm. The number of laminations is 60-240 for each mesh. These matrixes were inserted in matrix containers, and the ends were fixed in place by a sleeve. In order to decrease the influence on flow loss of immediate expansion and immediate contraction of the channel cross-section, the matrix containers were checked with the steady flow experiment, and tapers were attached at the inlet and outlet.

5.2 Equations

Figure 12 exhibits the time change of pressures P_1 and P_2 at both ends of a matrix (300-48-240) measured with an unsteady flow experiment. Momentary mass flow $(dm/dt)_i$ were calculated from the pressures per elapsed time $(P_1)_{i-1}$, $(P_1)_i$, $(P_2)_{i-1}$, $(P_2)_i$ of Figure 12, the average fluid velocity u_t in the matrix and the pressure drop per single gauze $(\Delta P)_i/n$ were found, and the coefficient of friction and Reynolds number were calculated.

Now if we find the mass flow of the compressed air which flows out in a minute time Δt from a reservoir which has volume V_R, then in order to find an average flow velocity at the matrix flow inlet, the following equation is obtained from the equation of state if the temperature change of the outflow air in a minute time is made very small.

$$\left(\frac{dm}{dt}\right)_i = \frac{V_R\{(P_1)_{i-1} - (P_1)_i\}}{RT_i\Delta t} \quad (9)$$

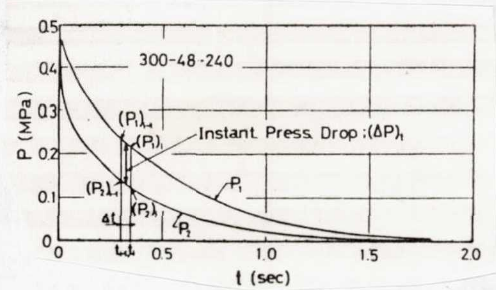


Figure 12. Unsteady pressure change.

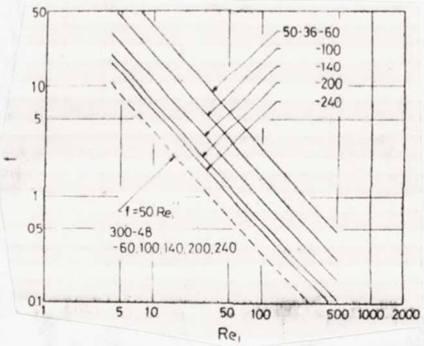


Figure 13. The changes of lamination number and coefficient of friction (arranged by aperture)

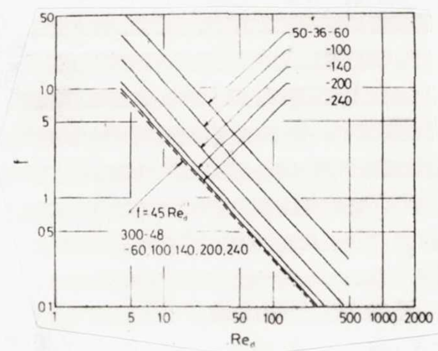


Figure 14. The changes of lamination number and coefficient of friction (arranged by wire diameter)

Therefore, if the frontal area of the matrix is A_f, then since the minimum free channel area is given by βA_f , the mean flow velocity u_t in the matrix will be given by the following equation:

$$u_t = \frac{1}{\beta A_f \rho_t}\left(\frac{dm}{dt}\right)_t = \frac{V_R\{(P_1)_{t-1}-(P_1)_t\}}{\beta A_f R T_t \rho_t \Delta t} \qquad (10)$$

Momentary pressure drop $(\Delta P)_t$ was calculated by the following equation:

$$(\Delta P)_t = \frac{(P_1)_{t-1}+(P_1)_t}{2} - \frac{(P_2)_{t-1}+(P_2)_t}{2} \qquad (11)$$

when the average flow velocity and pressure drop are calculated with equations (10) and (11), the minimum time Δt was set as 1 ms. Also, the same as in the steady flow experiment, the coefficient of friction and Reynolds number are described as follows:

$$f = \frac{(\Delta P)_t}{n} \Big/ \frac{1}{2}\rho_t u_t^2 \qquad (12)$$

$$R_{el} = \frac{l u_t}{\nu_t} \qquad (13)$$

$$R_{ed} = \frac{d_m u_t}{\nu_t} \qquad (14)$$

5.3 <u>Experimental results and discussion</u>

The following results were obtained by using the equations (10-14) to calculate Reynolds number and the coefficient of friction, based on the unsteady pressure change measured for each sample gauze.

5.3.1 The influence of lamination number

In order to study the influence of lamination number on the coefficient of friction, we laminated several layers of 50 mesh and 300 mesh gauzes and exhibited the changes in Figures 13 and 14.

The continuous lines in both figures are the changes in the coefficients of friction of 50 mesh, 36 wire gauzes, and the broken lines are the changes in the coefficient of friction of 300 mesh, 48 wire gauzes, when the number of laminations of the gauzes is changed between 60 and 240. We understand from both figures that in the case of 300 mesh gauze, which has a small pitch, this degree of change in laminations does not influence the coefficient of friction, and the coefficient of friction is described by a straight line; but in the case of 50 mesh, which has a large pitch, the frictional coefficient decreases gradually as the number of laminations increases.

/2213

5.3.2 Coefficients of friction of each mesh

Figure 15 is a study of the frictional coefficients of each mesh when the number of laminations is made constant (100 layers). We understand from Figures 13 and 14 that as pitch becomes small--in fact, as the mesh number becomes 50, 100,..., 300--the coefficient of friction becomes small.

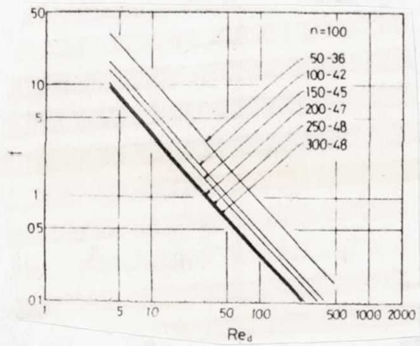


Figure 15. Coefficients of friction of each mesh (arranged by wire diameter)

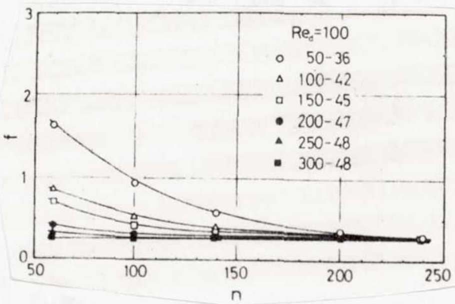


Figure 16. Changes in number of laminations and frictional coefficients (R_{ed} = 100)

5.3.3 <u>The influence of number of laminations (in the case when Reynolds number is made constant)</u>

Figure 16 exhibits the changes of frictional coefficients for the case when the number of laminations of each mesh is changed, when Reynolds number of each mesh is $R_{ed} = 100$. From the figure, in the case of 300 mesh gauze, there is no influence on the coefficient of friction by changing the laminations, but in the case of other meshes, there is a large influence as the gauze has a larger pitch. As the number of laminations increases, the coefficient of friction approaches the 300 mesh value, and it is understood that if a gauze has a small pitch, there is a smaller influence.

From the results of sections 5.3.1-5.3.3, the flow loss of several layers of laminated gauze is represented by mesh 300. Therefore, the empirical equation obtained by the unsteady flow experiments will be as follows:

In the case when hydraulic equivalent daimeter was set as aperture l

$$f = 50.0 R_{el}^{-1.1} \quad (4 \leq R_{el} \leq 500) \qquad (15)$$

When the diameter d_m was set as the hydraulic equivalent diameter

$$f = 45.0 R_{ed}^{-1.1} \quad (4 \leq R_{ed} \leq 500) \qquad (16)$$

Namely, we understand, from comparing Figures 13 and 14, if we choose wire diameter d_m rather than aperture l as the hydraulic equivalent diameter, the variance will be smaller. It is considered that resistance occurs when fluid particles pass through the openings of the channel areas of the gauze in steady flow. But in unsteady flow, the area of the gauze which casts a shadow related to the wire diameter becomes the resistance to flow. Therefore, it is understood that it is better for the coefficient of friction of laminated gauzes under unsteady flow to be described using the empirical equation (16) which chooses wire diameter d_m for the hydraulic equivalent diameter.

6. A comparison of the results of steady flow experiments and unsteady flow experiments

The following is a study of comparing the results obtained from steady flow and unsteady flow experiments.

(1) Number of laminations

Regarding gauzes of each mesh in steady flow, if the number of laminations is over 10, there is no change in pressure drop per single gauze. The relationship between frictional coefficient and Reynolds number was described by an empirical equation. However, in unsteady flow, if a very great number of laminations (compared to steady flow) is used and is changed from 60 to 240, the relationships of the coefficient of friction and of Reynolds number change for each mesh and for each number of laminations. However, as the mesh of the gauze approaches 300, the relationships of the coefficient of friction and of Reynolds number are not influenced by a change in the number of laminations.

This means that in the case of steady flow, a difference in dynamic pressures at the fluid inlet and outlet portions of laminated gauzes is not always found. But in the case of unsteady flow, it is considered that the dynamic pressure at the inlet and outlet portions of the laminated gauzes changes greatly, depending on the changes in filling air pressure in the reservoir. In this study, the flow velocity in gauze was represented by the flow velocity at the inlet and outlet portion of the flow. Namely, differences in the resistance of each mesh and differences in the number of laminations cause a difference in dynamic pressure between the inlet and outlet portions of the laminated gauzes. However, in the case of 300 mesh, which has a large resistance, there is almost no difference in dynamic pressure from changing the number of laminations to this degree if pressure is converted to per single gauze.

Empirical equations /2214

Figure 17 shows the comparison between the empirical equation obtained by the steady flow experiment and the equation obtained by the unsteady flow experiment.

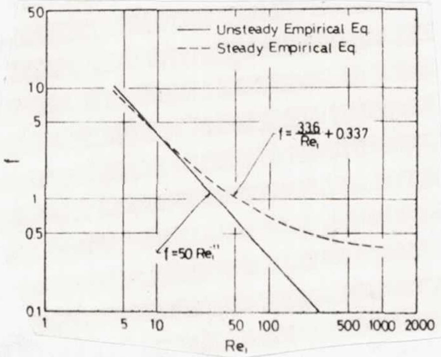


Figure 17. Comparison between steady flow empirical equation and unsteady flow empirical equation (arranged by aperture 1)

In the case when wire diameter d_m is chosen as the hydraulic equivalent diameter, a mutual relationship among both empirical equations is not found since the steady flow experimental values exhibit a large variance (Figure 9), so we will show Figure 17, in which the aperture 1 was chosen as the hydraulic equivalent diameter. From Figure 17, the frictional coefficients of both the empirical equation obtained by the steady flow experiment and that obtained by the unsteady flow experiment are equivalent in the low ranges of Reynolds number. On the other hand, as Reynolds number increases, a difference occurs among the two experiments and the steady value becomes higher than the unsteady value.

This shows that flow loss under steady flow is greatly influenced by the force of viscosity in areas of low flow velocity and that we cannot ignore the force of inertia as flow velocity increases. However, the influence of the force of inertia is considered to be small for flow loss under unsteady flow.

7. Conclusion

We took up gauze as material for a regenerator matix and performed steady flow and unsteady flow experiments on the flow loss of gauzes, from 10 mesh to 300 mesh, which are laminated in many layers over a wide range, and found empirical equations to give a coefficient of friction that are easy to use. The following is a summary of the results.

(1) Results of the steady flow experiment.

(i) Choosing aperture l instead of wire diameter d_m as the hydraulic equivalent diameter is easier to arrange and the coefficient of friction is given by

$$f = \frac{33.6}{R_{el}} + 0.337 \qquad (4 \leqq R_{el} \leqq 1\,000)$$

(ii) Since the channels of one gauze under steady flow are considered to be an aggregate of square cross-sectional tubes for which one side is aperture l, the flow in laminated gauzes is assumed to be a composition of the flow through sudden shrinkage of cross-section and flow through a sudden expansion of cross-section in inlet and outlet parts of the tube.

(2) Results of the unsteady flow experiment.

(i) Choosing wire diameter d_m instead of aperture l as the hydraulic equivalent diameter is easier to arrange and the coefficient of friction is given by

$$f = 45.0 R_{ed}^{-1.1} \qquad (4 \leqq R_{ed} \leqq 500)$$

(ii) The projected area of the portion of the gauze related to element wire diameter is considered to act as a resistance to the flow in laminated gauzes under unsteady flow.

(3) Comparing the steady empirical equation to the unsteady empirical equation in the case of steady flow, the influence of the force of viscosity is large for low flow velocity areas. As flow velocity increases, the influence of the force of inertia can no longer be ignored. But in the case of unsteady flow, the influence of the force of inertia is considered to be small.

At the end, we deeply thank Professor Emeritus Hideo Fujita, Professor Takio Ohya, Professor Toshiosuke Mashita and Professor Mitsusuke Itoh who directed this study. Also, we would like to mention that Mr. Kazuhiko Kanetoshi who was a graduate student (now at Nissan Automobile Company) aided in this study. This study was performed with the cooperation of the SR-173 sectional meeting of the Nihon Shipbuilding Research Association.

BIBLIOGRAPHY

(1) Edited by Nihon Machinery Institute, "Fluid Resistance of Conduit Runs and Ducts" (1979) 109, Nihon Machinery Institute.

(2) Ward-Smith, A. J., Internal Fluid Flow (1980), 463, Oxford Univ. Press.

(3) Walker, G., Sterling Engines (1980), 154, Oxford Univ. Press.

(4) Ishizaki and others, Mechanism Theory, No. 790-16 (Oct. 1979), 111.

(5) Tani and others, Mechanism Theory, No. 810-5 (April 1981), 132.

(6) Tohyama and others, Engine for Ships Institute Magazine, 15-6 (1980), 34.

(7) Kawakita and others, Automobile Technical Association theses, A 46-802 (1980), 275.

(8) Tong, L. S. and London, A. L. Trans. ASME, 79 (1957), 1558.

(9) Mori, Miyazaki, Machine Theory, 33-250 (1967), 956.

(10) Yamada and others, Low Temperature Engineering, 5-4 (1969) 216.

(11) Longwell, P. A. Mechanics of Fluid Flow, (1966), 73, McGraw-Hill.

DISCUSSION

(<u>Questions</u>) Yasujiro Kobashi (Engineering Dept., Hokkaido University)

(1) Was the mesh of the gauzes arranged completely arbitrarily or was some special arrangement chosen?

Is there any change of resistance that depends on the method of lamination?

(2) Why did you use $u = u_o/\beta$ instead of u_o for representing the speed? When the matrix flow is considered, it seems as though this is convenient, but it also appears that important information might be lost. The results from an increase in mesh, especially in the case of unsteady flow, and the decrease of the resistance coefficient is strange from a common sense point of view.

(3) I think the results of the unsteady experiment are influenced by the direction and speed of the opening and closing valves. Under what kinds of conditions did you perform this experiment?

Please explain the part, "the force of inertia is small for unsteady flow", mentioned on the right side of the 11th line of page 2214 since I think that it is the opposite of common sense.

(<u>Answers</u>) (1) The laminated gauzes were arranged completely arbitrarily. This is not only because it is difficult to arrange (laminate) mesh by putting many layers together, but also from the point of view of practicability.

Also, the change in resistance by your mentioned lamination method is thought to be caused by both sides of the lamination space and the mesh arrangement. Regarding the influence of lamination space, it is confirmed that resistance increases when the space is too wide (Figure 5). Also, when we think about the use of the

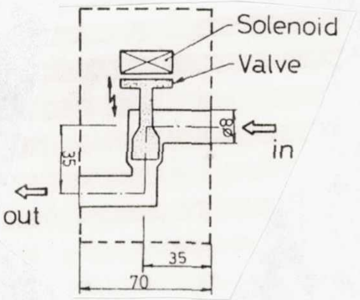
Sterling engine regenerator, since the decrease of invalid volume (void volume) is the most important condition, the case of close lamination becomes advantageous. We have not studied changes in resistance by mesh arrangement before but since the pitch of the applied gauze is small, it is difficult to arrange the mesh.

(2) Although choosing front flow speed u_o is considered as representing flow velocity, in order to study the resistance of one gauze, we used a representation of flow velocity u in which the flow velocity u_o of front flow is divided by the opening ratio β. Therefore, we do not think that important information is missing.

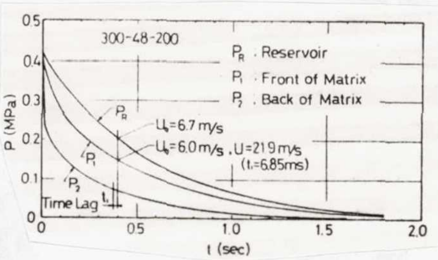
The decrease of coefficient of friction f with the increase of number of laminated layers and number of mesh in the unsteady flow experiment is, as you mentioned, thought to be strange; however, it is considered that this is influenced by the configuration of the flow channels in the front and back portions of the matrix. Also, the purpose of the unsteady flow experiment is to supply information in the case when the general properties of the matrix and the actual engine regenerator are considered. Therefore, the coefficient of friction found in this experimental equipment includes the influence of flow channel configuration in a rather small resistance matrix (mesh number and number of laminated layers are small). But since the influence of flow channel configuration becomes smaller compared to the matrix as the mesh number and the number of laminated layers increase, it is considered that the coefficient of friction decreases as the mesh number and laminated layer number increases as in Figure 16.

(3) As shown in the supplementary Figure 1, we used a solenoid operated valve which has a 15 ms opening and closing time and a valid flow channel of 15 mm^2 cross-sectional area.

As you mentioned, it is thought that the opening and closing directions of the valves, speed and cross-sectional area of the valid



Supplementary Figure 1.
Flow channel in solenoid-operated valve.



Supplementary Figure 2.
Non-steady pressure change and time delay.

channel greatly influence flow channel resistance, along with flow channel configuration in front of and in back of the matrix, in the unsteady flow experiment. However, as in the explanation of (2), the resistance of the matrix in this experiment is large and the influence of the valve is small compared to the matrix, so it can be ignored.

Also, regarding the influence of the force of inertia, for a high Reynolds number area in unsteady flow compared to a low Reynolds number area, the high Reynolds number area (this is the matrix front flow pressure around the place where the valve starts to open) becomes higher compared to back flow pressure (Figure 12). Therefore, it is thought that the penetrability of the matrix is better under steady flow, and the force of inertia becomes small.

(Questions) Tatsuaki Morimune (Engineering Dept., Tokyo Metropolitan University).

(1) Regarding the unsteady flow experiment, the fact that expansion conditions of the pressurized air towards atmospheric air (time until expanded, initial pressure of the filled air, resistance of gauze) differs is that, compared to pulsation flow, it is thought to respond to fluctuating cycle, amplitude and fluctuating wave forms of the flow. You arranged the frictional coefficient f by layer

number, mesh and pitch of the gauze, as in Figures 13-16. If there is an applied range described by non-constant values such as cycle or amplitude, please show it to me.

(2) In the case of unsteady flow in Figure 17, f decreases linearly with an increase of R_e. Can you tell me approximately the value of R_e for which f becomes constant?

(Answers) (1) As you mentioned in your question, the expansion conditions of the filled air towards atmospheric air are different /2216 for the unsteady flow experiment. However, the flow resistance of the matrix in this experiment in which many layers of gauze are laminated becomes very large so the flow becomes quasi-steady as the flow is restrained. The flow does not become one which is comparable to pulsation flow. Therefore, the applied range described by non-constant values such as fluctuating cycle, amplitude and fluctuating wave shape is undetermined.

(2) As I replied to Mr. Kobashi's question in my answer (3), for unsteady flow, as Reynolds number becomes higher, the influence of the force of viscosity becomes larger. As a result, the coefficient of friction changes linearly, but we have not studied the cases when Reynolds number becomes high. We would like to study it in the future.

(Questions) Tadashi Kushiyama (Yokohama Laboratory, Mitsubishi Heavy Industries Company).

I admire your study about the laminated gauzes of the regenerator which controls the efficiency of the Sterling engine. You completed the study of the characteristics of its flow loss very well.

I would like to ask you a few things about your unsteady flow experiment.

(1) When we think about unsteady flow, the pressure and flow of each part of a tube system are changed over time by the passage area ratios of the tube cross-sectional area and test matrix, reservoir and matrix, and matrix and the tube length until the tube edge. Therefore, the same quantity of state should be different at the same time.

How long is each tube used for this experiment?

I think accuracy will be improved if you use a very long tube for the unsteady flow test.

(2) I would like to know the reason why there is a difference between steady flow and unsteady flow characteristics. If we consider that the flow found from the pressure drop of the reservoir is because of the above mentioned reasons, how much difference is there?

(Answers) (1) The passage area ratio of the tube cross-sectional area (ϕ 8) and the test matrix (ϕ 20) in the unsteady flow experiment was made 0.16, and the tube lengths between reservoir and matrix and between matrix and tube edge were made to be 150 and 120 mm, respectively.

As you mentioned, the pressure and flow of each part of the tube system change with time, and the partial quantities of state differ. As mentioned in Figure 2, the flow velocity u_o before the matrix found by the change in pressure 0.4s after opening the valve is 6.0 m/s. Therefore, the flow velocity u in the matrix becomes 21.9 m/s. As a result, if flow velocity in the matrix is standardized, the time delay of pressure pickup (in a 150 mm space) becomes only 6.8 ms, and this is extremely small. Therefore, we think that the quantities of state at the same time almost do not change.

Also, as you mentioned, it is more accurate to use a long enough tube length for the unsteady flow experiment. However, as in Figure

16, we think that as mesh number and number of laminated layers increase, the resistance of the matrix increases. By ignoring the influence of flow channel configuration of the experimental equipment, we can measure the resistance of the matrix well with this experimental equipment.

(2) Since the volume (ϕ 66.8x500) of the reservoir is much larger than the tube which connects matrix and reservoir, a 1% difference occurs when comparing flows, whether or not the volume of the tube channel is considered.