RAREFIED GAS FLOW THROUGH A PIPE ORIFICE

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1. Introduction

Although the rarefied gas flow through an orifice has been investigated by Liepmann[1], Sreekanth[2], Smetana and others[3], the majority of these studies have been limited to the simple orifice in which the orifice diameter, d, is much smaller than D, the diameter of the chambers (or pipes) upstream and downstream of the orifice. In such geometries, there is no interaction between the pipe and the orifice and this situation simplifies the flow pattern and yields theoretical treatments[4] based on the kinetic theory.

From the practical point of view, however, there appear the cases in which the orifice is connected to the pipes of comparable diameters, not only as a flow measuring device but also as a part of the piping of a system. In such cases, it is questionable whether the results of the simple orifice are applicable or not. Bureau and others[5] analyzed the free molecular flow through a pipe orifice assuming a linear pressure distribution and discontinuous change at the orifice of infinitesimal thickness. Their results show that the conductance of the pipe orifice can be obtained from the result of the simple orifice by the adoption of a correction factor which is a function of the diameter ratio.

As for the continuum flow, on the other hand, there is Johansen's experimental studies[6] at low Reynolds number for the diameter ratios of 0.209 to 0.794, showing the linear relation between Reynolds number and discharge coefficient, when Reynolds number is less than 10.

The main purpose of the present investigation is to study the characteristics of the rarefied gas flow through a pipe orifice in the intermediate range of rarefaction between the free molecular flow and the continuum flow. Particular emphasis is placed on the interaction between the pipe and the orifice. It is hoped that the experimental results provide a suitable base for the practical estimation of conductance of the pipe orifice.

To describe the state of the flow, several parameters should be introduced and the classification of the state can be made by these parameters. One of the most fundamental parameter is a ratio of the degree of the non-uniformity to the degree of relaxation of the non-uniformity. The non-uniformity of macroscopic velocity which causes the momentum transfer is estimated by the velocity gradient du/dy where u is velocity component in x direction. The order of magnitude of the velocity gradient is U/L where U and L are characteristic velocity and length, respectively.

On the other hand, relaxation of the non-uniformity is related to the collision frequency $\nu = \overline{C}/\lambda$ where $\overline{C}$ is the mean molecular velocity and λ is the mean free path of the molecules. Therefore, the ratio is represented by

$$\xi = \frac{U}{\nu L} = \frac{U\lambda}{\overline{C}L} \fallingdotseq Kn \cdot M$$

where

$$Kn = \text{Knudsen number} = \lambda / L$$
$$M = \text{Mach number}$$

Beside this parameter, another important quantity is the ratio of the collision frequency between molecules and solid surface to the intermolecular collision frequency. The order of magnitude of the frequency of the molecule-surface collision is $\overline{C}/L$. Therefore, the ratio is

$$\frac{\overline{C}/L}{\nu} = \frac{\lambda}{L} = Kn$$

These parameters, ξ and Kn or M and Kn have to be introduced to take into account the degree of non-uniformity and the effect of rarefaction. In the present experimental study, Knudsen number is the dominant parameter, since Mach number is small and varies in a narrow range.

Nomenclatures

The following nomenclatures are mainly used:

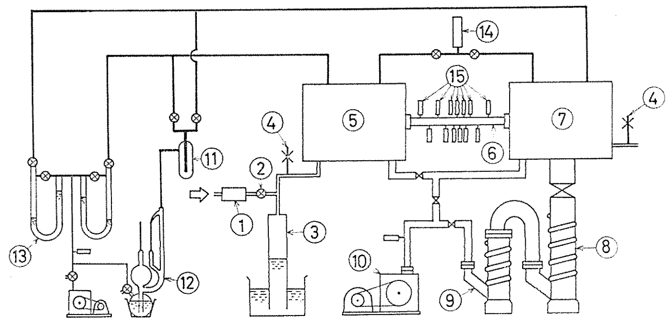
A = sectional area
a = radius
D = pipe diameter
d = orifice diameter
F = conductance
Kn = Knudsen number
L = total length
$\dot{m}$ = mass flow rate
p_h = pressure of the high pressure chamber
p_l = pressure of the low pressure chamber
p_f = pressure just before the orifice
p_b = pressure just behind the orifice
$\bar{p}$ = mean pressure
$\tilde{Q} = \dot{m}RT$: flow rate
R = gas constant
Re = Reynolds number
T = absolute temperature
$\overline{C} = \sqrt{8RT/\pi}$: mean molecular velocity
α = discharge coefficient
λ = mean free path
μ = coefficient of viscosity
ρ = density
$\Omega = \dot{m}\sqrt{T}/(p_f A_o)$: Perry's factor

subscripts
cf = continuum flow
fm = free molecular flow
o = orifice
p = pipe
pu = upstream portion of the pipe-orifice
pd = downstream portion of the pipe-orifice

The other nomenclatures than the above mentioned will be explained in the paper.

2. Experimental Apparatus and Measurements

The experimental layout is shown in Fig. 1. The main parts are a high



1. dryer
2. valve
3. vertical burette flow meter
4. leak valve
5. high pressure chamber
6. pipe orifice tested
7. low pressure chamber
8. oil diffusion pump
9. oil booster pump
10. rotary pump
11. liquid nitrogen trap
12. McLeod gauge
13. U-tube manometer
14. alphatron gauge
15. sensing elements of a Pirani gauge

FIG. 1. Experimental arrangement for conductance measurements of pipe orifices.

pressure chamber ⑤, a low pressure chamber ⑦ and a pipe orifice ⑥ which connects both chambers. These chambers are iron cylinders, 40 cm in diameter and 50 cm long, and their inner surfaces are nickel-plated to avoid outgas. The pumping system connected to the low pressure chamber consists of an oil-diffusion pump ⑧, an oil-booster pump ⑨ and a rotary pump ⑩. Automatic operation of the system is possible by use of pneumatic valves.

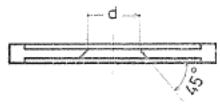
Air at room temperature flows into the high pressure chamber through a dryer ① containing silicagel and phosphorus pentaoxide and a vertical burette flow meter ③. Passing through the pipe orifice and the low pressure chamber, air is pumped out into the atmosphere. The pressures in the high and low pressure chambers are controled by leak valves attached to each chambers and measured by a standard McLeod vacuum gauge or U-tube manometers. The temperatures in both chambers are measured by thermo-couples and recorders. Care is taken to keep temperatures constant within 1°C through an experimental run.

The vertical burette flow meter consists of a Pyrex glass tube fixed vertically on a vessel which is filled with rotary pump oil or silicon oil. The glass tube is chosen among glass tubes in diameter 95.04 mm, 18.08 mm and 3.688 mm, depending on the flow rate of air. The operation of the flow meter is as follows: At first, air is admitted to the system from the atmosphere through a valve at the top of the flow meter. When the pressures in the chambers become sufficiently stable, the valve is closed and air in the glass tube is introduced into the high pressure chamber. The flow rate is measured by the height of the oil column raised for a certain time interval.

Use of the vertical burette flow meter required the calibration of the volume of the glass tube as a function of height of the oil column. This calibration was carried out by water or mercury, reading the height of the column by a cathetometer and weighing the liquid. The calibrated burette flow meter was used to measure the flow rate of a laminar pipe flow through a capillary tube of 0.993

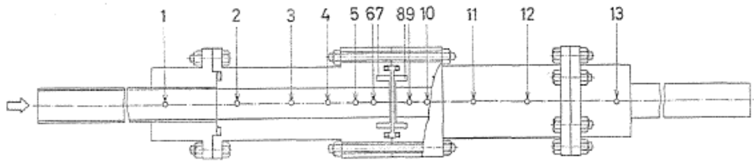
mm in diameter. The flow rate measured by the burette flow meter differs from the result obtained from the pressure drop in the capillary whthin 3 per cents.

Fig. 2 shows an orifice and the diameter ratio employed in the experiment. The orifice hole is formed by a part of a cone with a vertex angle of 90°. The sharpness of the orifice lip is insured by careful machining. Setup of the pipe orifice and the location of pressure taps are shown in Fig. 3. The diameter of each pressure tap hole is 0.5 mm and smoothness of the inner surface of the pipe was confirmed. Pressures at these taps were measured by Pirani gauges calibrated against a precision mercury McLeod gauge.



Nominal Diameter Ratio	0.8	0.6	0.4	0.2	0.1
Diameter Ratio d / D	0.798	0.598	0.400	0.203	0.0975
Area Ratio Ao / Ap	0.637	0.358	0.160	0.0412	0.00951

FIG. 2. An orifice and the diameter ratio employed in the experiment.



Location of Pressure taps

Pressure tap	1	2	3	4	5	6	7
-X (mm)	125.0	84.9	55.4	35.2	19.9	10.5	0

Pressure tap	8	9	10	11	12	13
X (mm)	1.5	11.5	21.7	46.7	76.6	126.2

(X: Distance from the Upstream Surface of the Orifice)

FIG. 3. Setup of the pipe orifice and the location of pressure taps.

3. Data Analysis and Results

3.1. Overall conductance of the pipe orifice

It is convenient to use a flow rate $\tilde{Q}$ defined as the product of the volume flow rate and the pressure at which it is measured:

$$\tilde{Q} = Q_V \cdot p \tag{1}$$

which is directly related to the mass flow rate by

$$\dot{m} = \frac{pQ_V}{RT} = \frac{\tilde{Q}}{RT} \tag{2}$$

if the gas is assumed to be perfect.

Conductance of a pipeline system is defined by

$$F=\frac{\tilde{Q}}{p_1-p_2} \tag{3}$$

where (p_1-p_2) is the pressure difference between the ends of the system.

Similarly, the conductance of a pipe orifice is expressed by

$$F=\frac{\tilde{Q}}{p_h-p_l} \tag{4}$$

where p_h and p_l are pressures at its ends, *i.e.* pressures in the high and low pressure chambers.

The pressure drop $p_1-p_2=p_h-p_l$ may be devided into three parts:

i) p_h-p_f=pressure drop in the upstream pipe
ii) p_f-p_b=pressure drop at the orifice
iii) p_b-p_l=pressure drop in the downstream pipe

where p_f and p_b are decided by the tangent to the pressure distribution curve in the upstream and downstream tubes as shown in Fig. 4. Corresponding to these partial pressure drops, the partial conductances are defined by

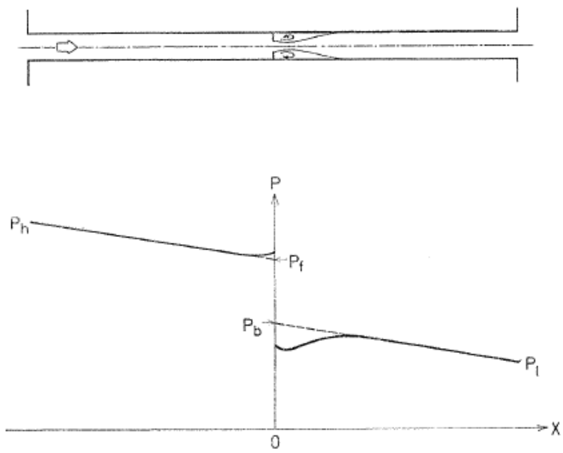


FIG. 4. Pressure distribution in a pipe orifice.

$$\left.\begin{aligned} F_{pu}&=\frac{\tilde{Q}}{p_h-p_f} \quad \text{for the upstream pipe}\\ F_o&=\frac{\tilde{Q}}{p_f-p_b} \quad \text{for the orifice}\\ F_{pd}&=\frac{\tilde{Q}}{p_b-p_l} \quad \text{for the downstream pipe}\end{aligned}\right\} \tag{5}$$

The overall conductance of the pipe orifice, F, is expressed by

$$\frac{1}{F}=\frac{1}{F_{pu}}+\frac{1}{F_o}+\frac{1}{F_{pd}} \tag{6}$$

In the free molecular flow regime, the overall conductance $(F)_{fm}$ has been analyzed by Bureau and others[5], obtaining the following formula:

$$(F)_{fm}=\sqrt{\frac{RT}{2\pi}}\,\frac{\pi}{4}d^2\left[\frac{1-\left(\frac{d}{D}\right)^2}{C}+\frac{3}{4}\frac{L}{D}\left(\frac{d}{D}\right)^2\right]^{-1} \tag{7}$$

where L is the distance of the pressure taps placed at the upstream and downstream pipes and C is nearly unity but weakly depends on the diameter ratio. Derivation of this equation is based upon the assumption of the linear pressure distribution in the pipes and discontinuous change at the orifice plate.

Equation (7) can be taken as a key stone of the data analysis, since there is no theoretical results for the continuum flow regime. Another reliable base for the data analysis is the Knudsen's semi-empirical formula[7] for the conductance of a circular pipe which agrees well with experimental results from the free molecular to continuum flow regime, provided the pressure ratio is very near to unity. This has been confirmed by the authors[8] for pipes of various materials for the Knudsen number less than 1. The Knudsen's formula is given by

$$\frac{F_p}{(F_p)_{fm}}=0.1472\frac{1}{Kn}+\frac{1+2.507\frac{1}{Kn}}{1+3.095\frac{1}{Kn}} \tag{8}$$

where $(F_p)_{fm}$ is the conductance of a circular tube in the free molecular regime, *i.e.*, $(F_p)_{fm}=\frac{2}{3}\pi(a^3/L)\overline{C}$, and the Knudsen number is based upon the pipe radius and the mean pressure, $\overline{p}=\frac{1}{2}(p_h+p_l)$.

Taking the diameter ratio and pressure ratio as parameters, the results of the measurements of the conductance of the pipe orifice are shown in Fig. 5 and 6. The dimensionless conductance $F/(F)_{fm}$ is plotted versus the inverse of the Knudsen number, $1/Kn$, where $(F)_{fm}$ is given by Eq. (7) and Kn is based upon the mean free path correspinding to the mean pressure $\frac{1}{2}(p_h+p_l)$ and the pipe radius, a. The mean free path is deduced from the relation

$$\mu=0.449\,\rho\overline{C}\lambda.$$

It is seen from Fig. 5–a for $d/D=0.8$ that the overall conductance increases very smoothly and monotonically from the free molecular flow to the continuum flow and differs little from the conductance of a simple pipe.

In the case of smaller diameter ratio, however, the overall conductance approaches to a limiting value as $1/Kn$ increases. The larger the pressure ratio, the smaller is the limiting value.

For a fixed diameter ratio, the curves for various pressure ratios form an envelope which coincides with the curve for the conductance when $p_h/p_l \fallingdotseq 1$. The departure from the envelope may be caused by the appearance of the wake behind the orifice plate and also by the compressibility. The larger the pressure ratio and/or diameter ratio, the smaller is the inverse of Knudsen number where

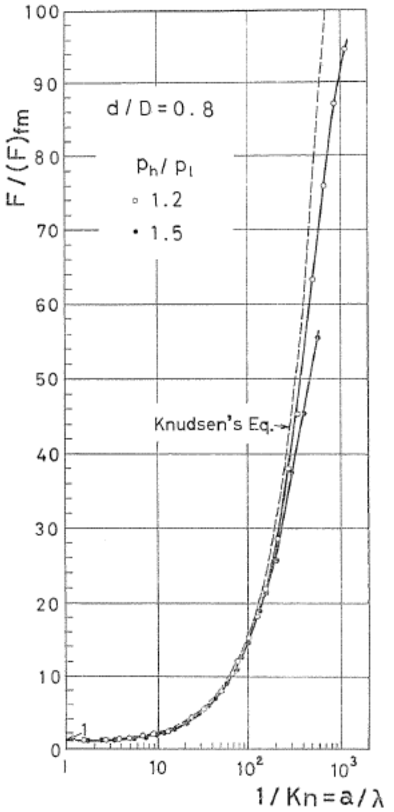


FIG. 5-a. Overall conductance of the pipe orifice ($d/D=0.8$).

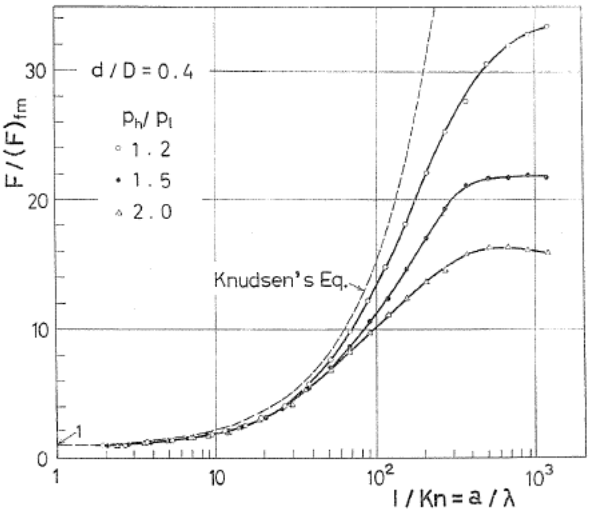


FIG. 5-b. Overall conductance of the pipe orifice ($d/D=0.4$).

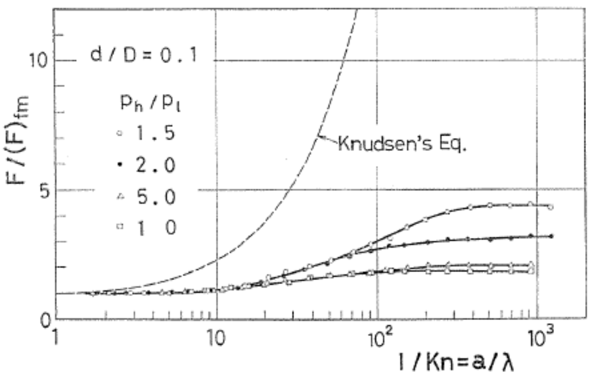


FIG. 5-c. Overall conductance of the pipe orifice ($d/D=0.1$).

the departure begins.

Fig. 6 shows the results for the case of fixed pressure ratios and it is generally seen that the tendency is similar as the case of the fixed diameter ratios.

As is evident from Fig. 5 and 6, the pressure ratio and diameter ratio have little effect on the conductance as far as $1/Kn<5$ and $(F/(F)_{fm})$ approaches to unity, showing the adequacy of Eq. (7) for the free molecular limit.

3. 2. Empirical Equation for the Overall Conductance

We consider an empirical equation for the overall conductance of the pipe orifice when the pressure ratio is so close to unity that the conductance curve coincides with the envelope to the family of curves as shown in Fig. 6.

It is ascertained experimentally that the Knudsen's formula (8) holds at the limit of $d/D=1$ and the envelopes to the conductance curves differ slightly from

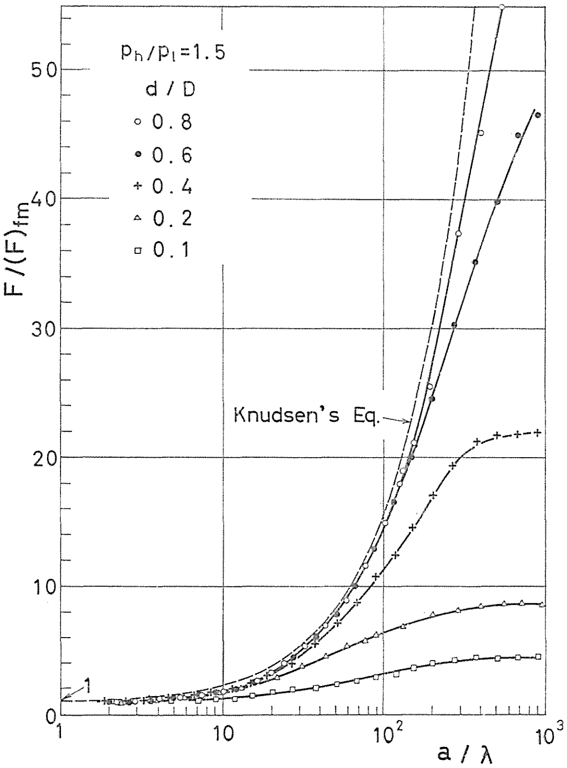


FIG. 6. Overall conductance of the pipe orifice ($p_h/p_l=1.5$).

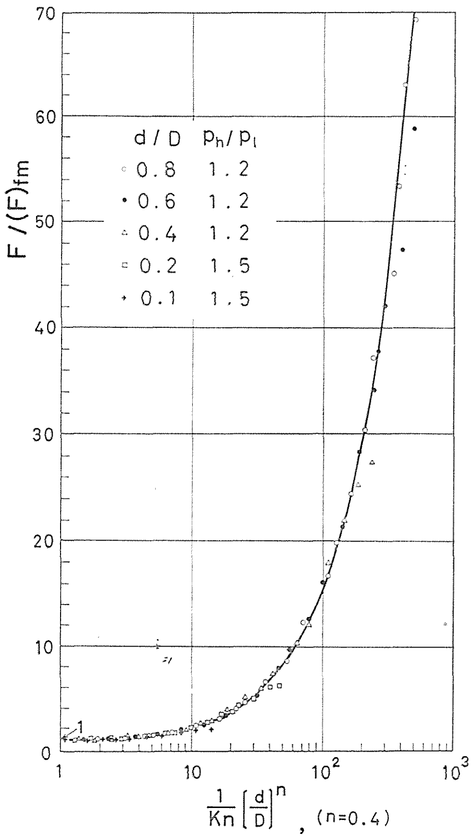


FIG. 7. Comparison of the mesured conductance with the empirical equation (9) when the pressure ratio is very close to unity.

the formula. Therefore, an empirical equation is proposed for the envelope, taking the diameter ratio as a parameter:

$$\frac{F}{(F)_{fm}}=0.1472\left\{\frac{1}{Kn}\left(\frac{d}{D}\right)^n\right\}+\frac{1+2.507\left\{\frac{1}{Kn}\left(\frac{d}{D}\right)^n\right\}}{1+3.095\left\{\frac{1}{Kn}\left(\frac{d}{D}\right)^n\right\}} \tag{9}$$

where $(F)_{fm}$ is given by Eq. (7). This equation involves Eq. (8) for the circular pipe as a case of $d/D=1$.

In Fig. 7, $F/(F)_{fm}$ is plotted versus $(1/Kn)\cdot(d/D)^n$ and the solid line represents Eq. (9) with $n=0.4$. It may be concluded that, as far as the pressure ratio is very close to unity, the overall conductance of the pipe orifice can be approximated by Eq. (9) introducing a parameter, $(1/Kn)\cdot(d/D)^n$.

3.3. Pressure Distribution

The pressure distributions of typical cases are shown in Fig. 8 where the

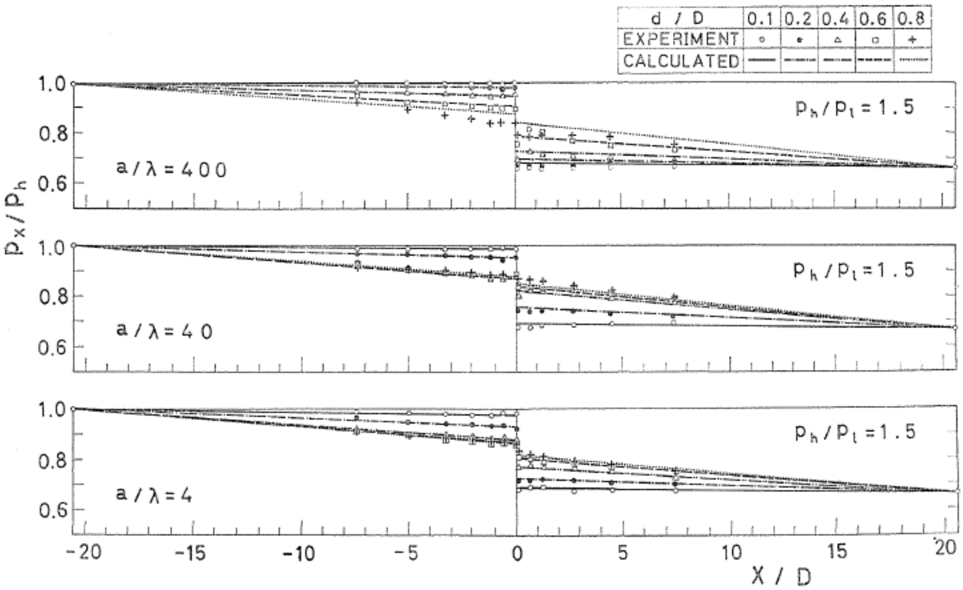


FIG. 8. Pressure distributions in the pipe orifice.

ordinate represents the nondimensionalized distance from the frontal surface of the orifice, X/D, and the abscissa represents p_x/p_h. Roughly speaking, the cases of $1/Kn=400$, 40 and 4 which are shown in the figure correspond to the continuum, transition and nearly free molecular flow. The experimental results are compared with the linear pressure distributions which are obtained by the determination of p_f and p_b (See Fig. 4) assuming that the upstream and downstream pipes are independent pipes whose conductances are governed by Eq. (8), mean pressures in the upstream and downstream pipes are taken as

$$(\bar{p})_{pu} = \frac{1}{2}(p_h + \bar{p})$$

$$(\bar{p})_{pd} = \frac{1}{2}(p_l + \bar{p})$$

where

$$\bar{p} = \frac{1}{2}(p_h + p_l).$$

In the upstream pipe, the effect of the orifice is so small that the measured pressure distributes linearly, showing fairly good agreement with the Knudsen's equation.

Across the orifice there appears a steep pressure drop: the larger the pressure ratio, the larger is the pressure drop. In the downstream pipe, the pressure distributions are more complicated. As far as the flow is nearly continuum, the pressure distribution has a valley behind the orifice and approaches asymptotically to the linear distribution predicted by the Knudsen's equation. As the flow becomes nearly free molecular, the valley disappears and the distribution is well approximated by the Knudsen's equation. It may be infered that the effect of the orifice is confined to its vicinity and the streamline is very similar to that of the ideal flow; the gas flows without separation even just behind the orifice.

As the density of the gas increases, intermolecular collisions become dominant and the mass flow is superposed on the free molecular flow which is caused by the molecular diffusion through the orifice.

3.4. Pure Conductance of the Orifice

The pure conductance of the orifice, F_o, is defined by Eq. (5) in terms of p_f

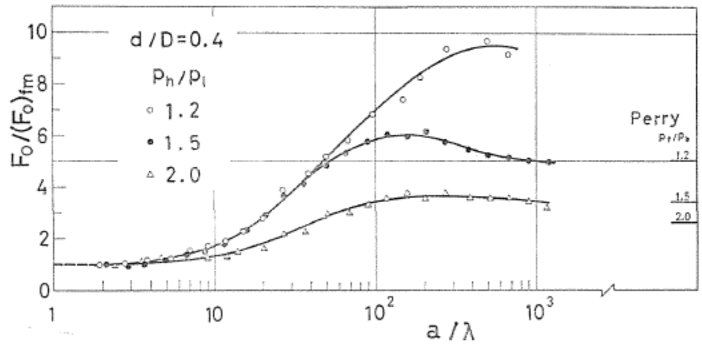


FIG. 9-a. Pure conductance of the orifice ($d/D=0.4$).

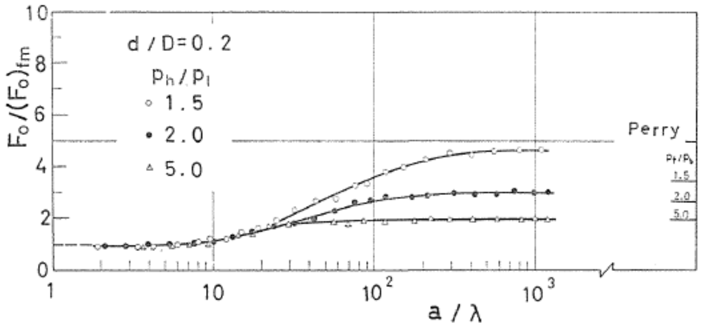


FIG. 9-b. Pure conductance of the orifice ($d/D=0.2$).

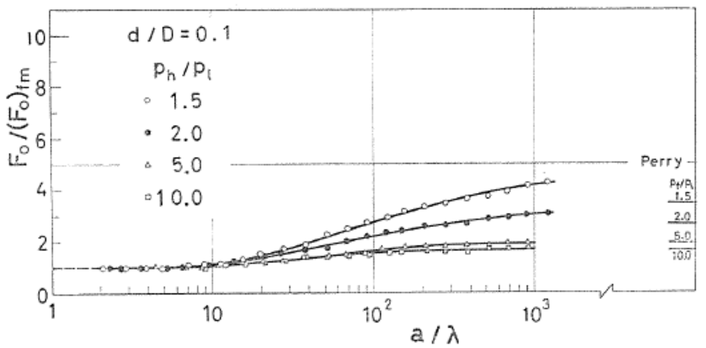


FIG. 9-c. Pure conductance of the orifice ($d/D=0.1$).

and p_b which are determined from the pressure distribution. Fig. 9 shows the relation between $F_o/(F_o)_{fm}$ and $1/Kn$ for the cases given in Fig. 5 and 6, where $(F_o)_{fm}$ is the conductance of a simple orifice (*i.e.*, $d/D=0$) in the free molecular flow, that is

$$(F_o)_{fm}=\frac{1}{4}\pi d^2\sqrt{\frac{RT}{2\pi}} \tag{10}$$

The pure conductance of the orifice shows nearly the same tendency as the overall conductance of the pipe orifice. For $1/Kn<5$, the pressure and diameter ratio have little effect and the conductance approaches to $F_o/(F_o)_{fm}=1$. For $1/Kn>5$, the conductance increases monotonically as far as p_h/p_l is very close to unity. And as the pressure ratio increases, it deviates from the smooth envelope and approaches to a limiting value which depends on the pressure and diameter ratio. The larger the pressure ratio and/or the smaller the diameter ratio, the smaller is the inverse Knudsen number where the transition begins. In Fig. 9, the limiting value for the continuum flow calculated by the Perry's equation[9] is shown. The Perry's equation for a simple sharp edged orifice is derived based on the relation between the mass flow rate and the pressure ratio for an ideal nozzle with an experimental modification factor. As shown in the figure for $d/D\leq 0.2$, the present experimental results agree fairly well with the Perry's limiting values as $1/Kn$ tends to infinity, while disagreement becomes appreciable when $d/D>0.2$. This disagreement can be attributable to the strong interaction between the pipe flow and the orifice flow and to the complicated flow pattern.

3.5. Comparison of the measured conductance with the Theoretical prediction

In Table 1, the measured conductances F are compared with the theoretical prediction calculated in the following ways:

TABLE 1. Comparison of the measured conductance with the theoretical prediction ($p_h/p_l=1.5$).

d/D	0.8	0.6	0.4	0.2	0.1
$1/Kn$	550	509	511	557	510
F (l/s)	46.6	31.9	15.8	4.19	0.885
$(F)_{cf}$ (l/s)	41.3	26.2	13.1	3.53	0.836
$1/Kn$	1.87	2.04	2.03	2.47	2.10
F (l/s)	0.812	0.754	0.726	0.508	0.190
$(F)_{fm}$ (l/s)	0.809	0.777	0.706	0.475	0.192

(a) Continuum flow

$$\frac{1}{(F)_{cf}}=\frac{1}{(F_{pu})_{cf}}+\frac{1}{(F_o)_{cf}}+\frac{1}{(F_{pd})_{cf}} \tag{11}$$

where $(F_{pu})_{cf}$ and $(F_{pd})_{cf}$ are expressed by the Poiseuille flow,

$$\left.\begin{aligned}(F_{pu})_{cf}&=\frac{\tilde{Q}}{p_h-p_f}=\frac{\pi a^4}{8\mu(L/2)}(\bar{p})_{pu}\\(F_{pd})_{cf}&=\frac{\tilde{Q}}{p_b-p_l}=\frac{\pi a^4}{8\mu(L/2)}(\bar{p})_{pd}\end{aligned}\right\} \tag{12}$$

and $(F_o)_{cf}$ is calculated in terms of the Perry's semiempirical formula.

(b) Free molecular flow

$$\frac{1}{(F)_{fm}}=\frac{1}{(F_{pu})_{fm}}+\frac{1}{(F_o)_{fm}}+\frac{1}{(F_{pd})_{fm}} \tag{13}$$

where

$$(F_{pu})_{fm}=(F_{pd})_{fm}=\frac{2}{3}\pi\frac{a^3}{(L/2)}\overline{C} \tag{14}$$

and $(F_o)_{fm}$ is given by the conductance for a simple orifice, *i.e.*, Eq. (10).

The comparison shows that, for the free molecular flow, the experimental values agree fairly well with the calculated ones. On the other hand, agreement is not satisfactory for the continuum flow.

It is interesting to estimate how large the increment of the pipe resistance by the insertion of an orifice is. Table 2 shows the ratio of the overall resistance to the simple pipe resistance. It is clarified that the effect of the orifice in the free molecular flow is much smaller than that in the continuum flow. For the case of $d/D=0.8$, for instance, the existence of the orifice increases the resistance only 6% in the free molecular flow but 67% in the continuum flow. This tendency is strengthened as the diameter ratio decreases. Therefore, for smaller diameter ratio than 0.2, the resistance of the pipe portion can be neglected compared with that of the orifice. In other words, such a pipe orifice can be considered as a simple orifice.

TABLE 2. The ratio of the overall resistance to the simple pipe resistance.

d/D	0.8	0.6	0.4	0.2	0.1
$(F_p)_{cf}/(F)_{cf}$	1.67	2.44	4.90	19.8	76.7
$(F_p)_{fm}/(F)_{fm}$	1.06	1.11	1.25	2.01	5.04

3. 6. *Discharge Coefficient*

In the hydraulic engineering, the discharge coefficient of a pipe orifice, α, is used to express the mass flow rate:

$$\dot{m}=\alpha\frac{\pi}{4}d^2\sqrt{\frac{2\rho_f(p_f-p_b)}{1-(d/D)^2}} \tag{15}$$

where p_f and p_b are measured by corner taps and ρ_f is the density of the gas at the frontal surface of the orifice. Such a discharge coefficient can be expressed in terms of the conductance F and $\widetilde{Q}$ as follows:

$$\alpha=\frac{4\widetilde{Q}}{\pi d^2}\sqrt{\frac{1-(d/D)^4}{2RT_fp_f(p_f-p_b)}} \tag{16}$$

For the continuum low Reynolds number flow, Johansen[6] investigated experimentally the variation of α with respect to the diameter ratio and Reynolds number which is defined by

$$Re=\frac{4\dot{m}}{\pi d\mu}$$

According to his results, α is independent of the diameter ratio for $Re<10$ and is proportional to $\sqrt{Re}$.

In order to compare the present experimental results with those of Johansen,

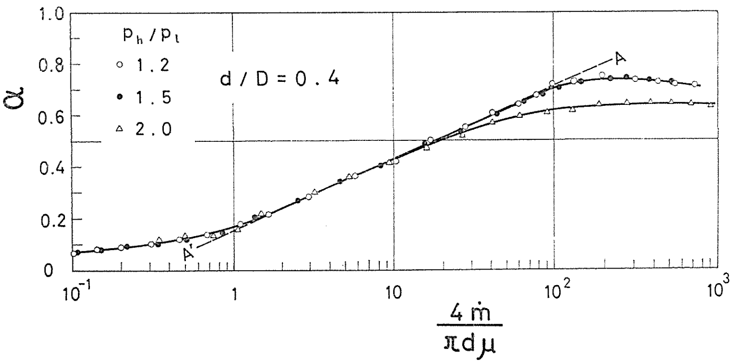


FIG .10-a. Discharge coefficient ($d/D=0.4$).

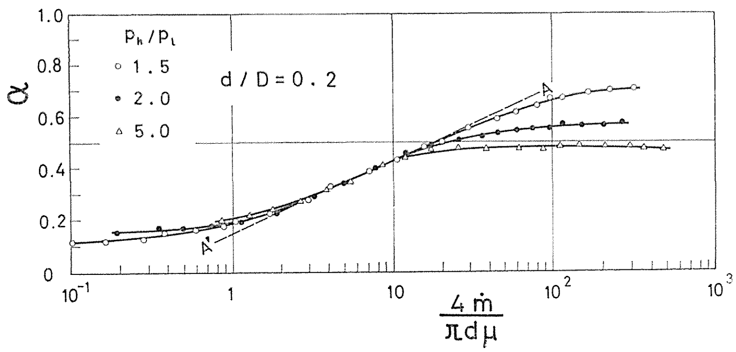


FIG. 10-b. Discharge coefficient ($d/D=0.2$).

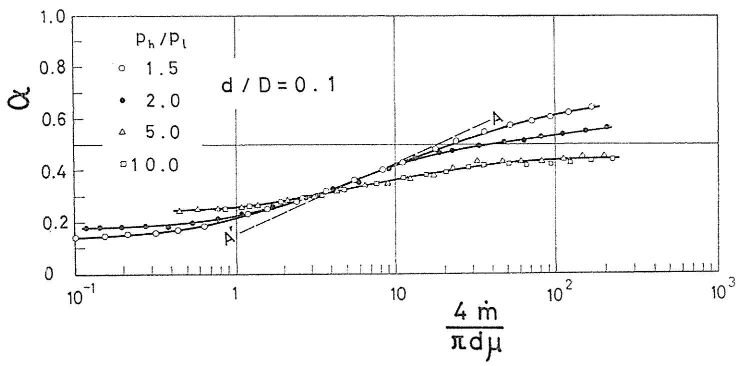


FIG. 10-c. Discharge coefficient ($d/D=0.1$).

α is plotted versus Re in Fig. 10, in which the dotted line A-A′ shows the relation, $\alpha \propto \sqrt{Re}$. As Re decreases the experimental curve deviates from the line A-A′ because of the rarefaction effect. On the other hand, the deviation at larger Re may be attributable to the effect of the wake behind the orifice and also to the compressibility.

4. Concluding Remarks

The resistance of the sharp edged pipe orifice having diameter ratio in the range of 0.2 to 0.8 was measured experimentally for Knudsen number of 1 to 0.001 and for pressure ratios of 1 to 10. Pressure distribution along the pipe was measured to estimate the effect of the orifice on the pipe flow.

The results may be summarized to the following conclusions:

(1) For $1/Kn<5$, the diameter ratio and pressure ratio have little effect on the overall conductance of the pipe orifice. At the free molecular limit, the overall conductance can be expressed by the Bureau's equation. On the other hand, for $1/Kn>5$ the overall conductance increases monotonically as far as the pressure ratio is very close to unity. As the pressure ratio increases, however, it deviates from the envelope which is formed by the family of conductance curves for various pressure ratios and approaches assymptotically to a limiting value. The smaller the diameter ratio and/or the larger the pressure ratio, the smaller is the inverse Knudsen number where the deviation from the envelope begins.

(2) The envelope of the overall conductance curve for $p_h/p_l \fallingdotseq 1$ can be well approximated by the empirical equation (9) introducing a parameter, $(1/Kn)(d/D)^n$.

(3) The overall resistance for the free molecular flow can be calculated by the simple addition of the pipe resistance, $(1/F_{pu})_{fm}$ and $(1/F_{pd})_{fm}$ and the resistance of the simple orifice, $(1/F_o)_{fm}$. For the continuum flow, the overall resistance is roughly approximated by the Poiseuille flow and Prrry's equation.

(4) The pipe orifice of $d/D \leq 0.2$ can be considered as a simple orifice.

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