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An Investigation of Impinging Jet*

(Experiments by Air, Hot Air and Carbondioxide)

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This is an investigation of flow characteristics of a wall jet produced by gases impinging on a plate from an axisymmetric nozzle. Air, hot air, and carbondioxide were used, and the distances from the nozzle to the plate were fixed equal to the nozzle diameters.

Experiments were carried out at exit Reynolds numbers from 1300 to 21000, for various nozzle diameters and exit velocities. Velocity, temperature and concentration profiles become similar at various distances X from the impinging center, for the same exit Reynolds number. Experimental relations between X and maximum values of temperature, concentration and velocity were obtained.

Mixing length, eddy viscosity and entrainment of surrounding air were given in comparison between impinging and free jets.

1. Introduction

A few characteristics of a wall jet produced by the impinging jet on a flat plate have been reported⁽¹⁾⁽²⁾, but there are many unknown problems in this flow because of its complexity. Usually, the impinging jet is divided into three regions, that is, the regions of free jet, impinging jet and wall jet, but those studies reported are mainly on the behaviors within the region of impinging jet from the view points of fluid mechanics and heat transfer.

This paper deals with the wall jet region produced by an axisymmetric nozzle and a flat plate. The momentum, heat and mass transfers of the flow were measured in this region. When the distance H from the nozzle exit to the plate is large, the region of free jet as well as one of impinging jet becomes large. And the characteristics of this free jet region are essentially the same as those without impinging plate.

Since in this experiment much attention is paid to the analysis of flow of wall jet region, the ratio of the distance from the nozzle exit to the plate H to the nozzle diameter D_0 is set at 1, ($H/D_0=1$). Therefore, the regions of free and impinging jets are very small and all most region of the flow consists of a wall jet.

This flow model may be applied to that in the fields of combustion and freezing industry. The reason for adopting the

above-titled "impinging jet" is that the issuing condition of nozzle is taken as one of the parameters of the flow.

Nomenclature

a, b, c	empirical constants
B_0	distance from plate to position of maximum value at any section
$B_{\frac{1}{2}}$	distance between positions of maximum value and those of half maximum value in outer layer at any section
D_0	nozzle pipe diameter
H	distance from plate to nozzle exit
K	empirical constant
$L_{\frac{1}{2}}$	$B_0 + B_{\frac{1}{2}}$
lu	mixing length
Q	mass flow rate at any section
R	$(X^2 + Z^2)^{\frac{1}{2}}$
Re_0	Reynolds number of nozzle pipe exit flow = $\bar{W}_0 D_0 / \nu$
Re_b	Reynolds number of boundary layer flow = $U m B_{\frac{1}{2}, u} / \nu$
T	temperature
U	X component of mean flow velocity
u	X component of fluctuating velocity
W	Z component of mean flow velocity
X, Z	coordinates
α	exponent
r	specific weight
ϵ	eddy kinematic viscosity
A	molar fraction
ν	kinematic viscosity
ρ	density

Subscripts

m	maximum
o	nozzle exit
t	temperature
u	flow velocity
A	concentration

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2. Experimental Apparatus

A stainless steel flat plate with diameter of 500 mm is located horizontally, and a nozzle with inner diameter D_0 is set up perpendicular to the plate. One side of the plate on which the jet is impinged is made smooth, and another is water-cooled to keep temperature on the plate constant.

For experiments with air jet, the air is supplied from the air compressor through a pressure regulating valve and its flow rate is measured by an orifice flow meter. As the nozzle pipe is long enough compared with D_0 , a fully developed pipe flow is produced at the exit. Three different nozzle pipes with inner diameters of 10, 4.2 and 1.0 mm are used.

For those with the hot air jet, the air is heated by an electric heater set in a heating chamber, which is placed between the nozzle pipe and the compressor. The temperature of hot air is varied by controlling the electric current of the heater. In these experiments, the pipes are covered with insulator.

For experiments with the carbon-dioxide gas jet, the gas is conducted from a CO_2 gas cylinder and its flow rate is controlled by a reducing valve.

The flow velocity of air jet is measured by a hot wire anemometer composed of a tungsten wire in diameter of 10μ . Both of mean and r.m.s. values of fluctuating velocity distributions are recorded on a dual channel XY-recorder against their position.

The temperature is measured with a copper-constantan thermo-couple in diameter of 0.1 mm. The thermo-couple is stretched straight so that the junction may be located at the center of the stem. The temperature distributions are recorded on the XY-recorder.

Molar concentration of carbon-dioxide is measured with gaschromatography. Sampling probe consists of ten tubes in inner and outer diameters of 0.4 and 0.8 mm, respectively, which are arranged at intervals of 2 mm.

The velocity profiles of hot air jet and carbon-dioxide gas jet are obtained from the total pressure measured with an impact tube taking into consideration the density at each point.

All measurements are made by using a traverse equipment, which can be rotatable around the center of nozzle pipe and can be traversed in radial and axial directions, independently. Moving distances in X and Z directions and rotating angles are recorded on the XY-recorder.

3. Experimental Results

3.1 Velocity distributions

A typical flow model of the impinging jet is shown in Fig. 1, in which X is taken as a radial coordinate from the impinging point along the plate and Z as a

coordinate perpendicular to X, and $B_{0,u}$ and $L_{\frac{1}{2},u}$ are the distances from the plate to the position of maximum velocity U_m and the position at which the velocity becomes half of U_m , respectively.

Fig. 1 Schematic representation of flow field of impinging jet.

The gas issued from nozzle impinges on the plate and diffuses in X and Z direction along the plate. The nondimensional velocity distributions have a similar profile as shown in Fig. 2 in the fully developed turbulent flow, exit Reynolds number R_0 being 15,600 in this case. When the flow becomes laminar corresponding to a small Reynolds number, the dimensionless velocity profile has a different shape from that of the turbulent flow as shown in Fig. 3, which corresponds to the Reynolds number of 1,340.

$L_{\frac{1}{2},u}$ and $B_{0,u}$ have linear relations with X as shown in Fig. 4, which are given by

Fig. 2 Velocity profiles, turbulent flow.

Fig. 3 Velocity profiles, laminar flow.

Fig. 4 Linear relationships between the boundary layer thickness and X .

$$L_{1/2,u} = a_u X \quad (1)$$

$$B_{0,u} = b_u X \quad (2)$$

where a_u and b_u are empirical constants. Although a_u and b_u depend upon the exit Reynolds number, they are independent upon the nozzle diameter for the same Reynolds number as shown in Fig. 5. The variations

Fig. 5 Relations between proportional constants and exit Reynolds number.

of a_u and b_u with R_0 are caused by the development of the boundary layer thickness on the plate surface.

Putting $L_{1/2,u} - B_{0,u} = B_{1/2,u}$, the spread of $B_{1/2,u}$ in the direction of X may be represented, as a linear function of X , by

$$B_{1/2,u} = c_u X \quad (3)$$

The values of c_u are nearly constant independently of the Reynolds number.

In Fig. 6, the spatial distribution

Fig. 6 Diagrams of constant velocity fluctuations.

of the velocity fluctuation is shown in the case of turbulent flow which corresponds to the exit Reynolds number of 6350. In the figure, the straight lines of $R(U_{max})$ and $R(\frac{1}{2}U_{max})$ represent the positions at which U becomes U_m and $\frac{1}{2}U_m$, respectively. It is obvious that the turbulent intensity is almost constant over a considerable range of Z at any X -section in the flow.

Fig. 7 Decay of maximum and fluctuating velocities.

The decreases of U_m and $\sqrt{u'^2}$ along R are shown in Fig. 7, where $R = (X^2 + Z^2)^{1/2}$. R is nearly equal to X , U_m and $\sqrt{u'^2}$ are represented as functions of X , which are given by $U_m \propto X^{\alpha_u}$ and $\sqrt{u'^2} \propto X^{\alpha'_u}$, respectively.

Fig. 8 Relation between the exponent and boundary layer Reynolds number.

Fig. 8 shows the relation between the exponent α_u and the boundary layer Reynolds number referred to $B_{1/2,u}$ and U_m . The values of α_u at high Reynolds number coincide well with Glauert's result⁽³⁾ which is obtained by assuming a linear relation between exponents a and b in the equations of $U \propto X^a$ and $L_{1/2,u} \propto X^b$.

According to Prandtl's hypothesis⁽⁴⁾, mixing length l_u is given by the following expression.

$$l_u = \sqrt{u'^2} / \left| \frac{\partial U}{\partial Z} \right| \quad (4)$$

Mixing length l_u obtained at the position of $Z = L_{1/2,u}$ has a linear proportionality to X for various flow conditions of the jet as shown in Fig. 9, in which the mixing length for free jet is also shown for comparison. In the case of free jet, the axial distance from nozzle exit X and the half radius at which the velocity becomes half of the maximum velocity are used for

Fig. 9 Linear relationship between the mixing length and radial distance.

calculating mixing length. Fig. 9 shows that there is no difference in the mixing length between free and impinging jets.

Fig. 10 Relations between eddy viscosities and radial distance.

Fig. 10 shows the relation between the eddy viscosity and \$X\$. The eddy viscosity is calculated with the following equation

$$\epsilon = l u^2 \left| \frac{\partial U}{\partial Z} \right| \quad (5)$$

It is found from the figure that the eddy viscosity changes with \$R_o\$ and \$X\$, and that the eddy viscosity of free jet is much larger than that of impinging jets under consideration.

Fig. 11 Decay of maximum velocities.

The decay of the maximum velocity \$U_m\$ along \$X\$ is shown in Fig. 11 for the free and impinging jets. The decay of \$U_m\$ for the impinging jets is represented by the following empirical equation

$$U_m/W_o = K_u (X/D_o)^{\alpha_u} \quad (6)$$

While the exponent \$\alpha_u\$ changes with \$R_b\$ in the region of small boundary layer Reynolds number, it approaches to a constant which is in the range of \$-1.13 \sim -1.10\$ in the region of \$R_b\$ greater than 300. By the way, the flow defined by \$R_b = 300\$ is obtained by the conditions at the nozzle exit of either \$R_o = 6,000\$ with \$D_o = 10\$ mm or \$R_o = 10,000\$ with \$D_o = 1\$ mm. In addition, the experiment by Bakke⁽⁵⁾ gives a value of \$-1.12\$ for the exponent at high Reynolds number. Though the experimental constant \$K_u\$ in Eq. (6) changes with the flow condition, its details will be described later.

3.2 Temperature distribution

The temperature and velocity distributions established in hot air impinging jet are shown in Fig. 12(a) and (b), respectively.

Fig. 12 (a) Temperature distribution.

Fig. 12 (b) Velocity distributions.

tively, in which \$T_m\$ and \$L_{1/2,T}\$ represent the maximum temperature and the distance from the plate to the position where \$T = \frac{1}{2}T_m\$ in outer layer, and \$T_a\$ is the atmospheric temperature. The exit Reynolds number is referred to the kinematic viscosity at the nozzle exit. From these figures, the temperature distributions have a similar profile as the velocity distributions.

Now, assuming a linear proportionality between $L_{\frac{1}{2},t}$ and X as

$$L_{\frac{1}{2},t} = a_t X \quad (7)$$

the empirical constant a_t in Eq. (7), as

Fig. 13 Relations between the proportional constants and exit Reynolds number.

shown in Fig. 13, changes with the flow condition just as a_u in the velocity distributions. $B_{0,t}$ and $B_{\frac{1}{2},t}$ defined in the same way as $B_{0,u}$ and $B_{\frac{1}{2},u}$ in the velocity distributions, have also the following linear relations given by

$$B_{0,t} = b_t X \quad (8)$$

$$B_{\frac{1}{2},t} = c_t X \quad (9)$$

Proportional constants b_t and c_t are also shown in Fig. 13 as a function of the exit Reynolds number. The values of b_t and c_t show a considerable difference from b_u and c_u in Fig. 5. This difference is caused by the change in the outer temperature layer thickness with the Reynolds number, while the inner layer thickness does not change. This character is contrary to that of velocity.

Fig. 14 and 15 show the experimental relations between the nondimensional maximum temperature $(T_m - T_a)/(T_0 - T_a)$ and

Fig. 14 Decay of maximum temperature.

Fig. 15 Decay of maximum temperature.

the nondimensional radial distance from the impinging center X/D_0 . From these figures, the following empirical equation for temperature decay is obtained.

$$\frac{T_m - T_a}{T_0 - T_a} = K_t \left(\frac{X}{D_0} \right)^{\alpha_t} \quad (10)$$

The proportional constant K_t and exponent α_t in this equation are equal to 1.2 and -1.13 for $R_0 \geq 6,240$ and 0.9 and -1.06 for $R_0 \leq 4,510$, respectively.

The velocity profiles of hot air jet are the same as ones of air jet without temperature difference. Furthermore, the proportional constant a_u for the hot air jet is 0.08 at $R_0 = 12,000$, which is nearly equal to the result in Fig. 5.

Comparison of the boundary layer thickness between temperature and velocity made for the turbulent flow region shows that the proportional constant for temperature a_t is much larger than that for velocity a_u , which indicates that the temperature diffuses more rapid than the momentum.

3.3 Concentration distribution

The distributions of molar concentration of carbon-dioxide across the sections of X are shown in Fig. 16. As the maximum concentration A_m exists on the surface of the plate, the profiles of concentration distribution are quite different from

Fig. 16 Distribution of molar concentrations of CO_2 gas.

those of velocity and temperature. Denoting $B_{\frac{1}{2},A}$ a distance from the plate to the position of half of A_m , the relation between $B_{\frac{1}{2},A}$ and X is given in the same way as the other cases, that is;

$$B_{\frac{1}{2},A} = a_A X \quad (11)$$

The proportional constant a_A in Eq. (11) changes with the exit Reynolds number Ro

Fig. 17 Relation between the proportional constant and exit Reynolds number.

as shown in Fig. 17, and these values are slightly larger than a_t in Fig. 13, and much larger than a_u just as in the case of hot air jet.

The decay of the maximum concentration along X is given in a rather simple

Fig. 18 Decay of maximum concentration of CO₂ gas.

form as shown in Fig. 18, which is given empirically by the following expression within the range of $3,500 \leq Ro \leq 21,000$.

$$A_m = 1.5 \left(\frac{X}{D_0} \right)^{-1.0} \quad (12)$$

The velocity distributions of carbon-dioxide jet measured by an impact tube are the same as those of air jet without temperature difference.

4. Entrainment of surrounding air by jet

Mass flow rate of the wall jet across any section of X is given by

$$Q = 2\pi \int_0^\infty r U X dz \quad (13)$$

where r and U are the local specific weight of gas and the local flow velocity, respectively. In addition, the exit flow

rate from the nozzle tube is given by

$$Q_0 = \frac{1}{4} \pi D_0^2 \bar{W}_0 r_0$$

Mass flow rate Q increases toward the downstream of the jet. Fig. 19 shows the

Fig. 19 Comparison of mass flux for impinging jet and for free jet.

relation between Q/Q_0 and X/D_0 .

The experimental results of Q/Q_0 against X/D_0 agree fairly well with Hertel's quasi-empirical equation⁽⁶⁾ except for those at the large X/D_0 where the precise measurement of local velocity is difficult because of a small velocity gradient. Although, in the case of carbon-dioxide gas jet, small values of Q/Q_0 may be expected compared with those of air jet, the differences in these values are not large, and may be considered to be within the experimental errors. The experimental results of free jet are also shown in Fig. 19 for reference, which agree well with the equations given by Hertel⁽⁶⁾ and Ricou & Spalding⁽⁷⁾.

5. Considerations

5.1 Empirical equation for decay of U_m

Decays of T_m and A_m along X have already given by simple empirical equations, but equation of velocity decay along X has rather complicated form, because the proportional constant K_u varies with the flow condition of jet.

Putting $\tilde{U}_m = U_m/\bar{W}_0$ and $X = X_0$ where $\tilde{U}_m$ becomes unity, the proportional constant K_u in Eq. (6) is represented as $(X_0/D_0)^{-\alpha_u}$. Then, Eq. (6) becomes

$$\tilde{U}_m = (X_0/X)^{-\alpha_u} \quad (14)$$

and it gives the expression of $X_0 = X \tilde{U}_m^{-1/\alpha_u}$ which yields, by using the relation of $B_{\frac{1}{2},u} = c_u X$ and the definitions of Ro and R_b , to the following equation for X_0/D_0

$$\frac{X_0}{D_0} = \left(\frac{R_b}{c_u Ro} \right)^{-1/\alpha_u} \left(\frac{X}{D_0} \right)^{(\alpha_u+1)/\alpha_u} \quad (15)$$

here, $-\alpha_u$ is larger than unity as shown in Fig. 8.

Relation between Ro and Rb is represented by $Ro \propto Rb^2$ in the region of $Rb <$

Fig. 20 Relation between Rb and Ro .

500 as shown in Fig. 20. The entrainment of surrounding air by jet being represented by $Q/Q_0 \propto X$ for the same nozzle diameter Do , and the dimensionless velocity distribution referred to $B_{\frac{1}{2},u}$ and U_m having a similar profile, the amount of entrainment is given by $Q \propto B_{\frac{1}{2},u} U_m X$. Therefore, $Do^2 \bar{W}_0 \propto U_m B_{\frac{1}{2},u}$ is obtained. Furthermore, according to the relations of $U_m \propto (DoX)^{-1}$ and $X \propto B_{\frac{1}{2},u}$, $Ro \propto Rb^2$ is also obtained. Substituting the last equation into Eq. (15), X_0/Do is given by

$$\frac{X_0}{Do} = Rb^{\frac{1}{\alpha_u}} \left(\frac{X}{Do} \right)^{(\alpha_u + 1)/\alpha_u} \quad (16)$$

Since α_u has a negative value, Eq. (16) shows that X_0/Do decreases with increasing in Rb , while X_0/Do increases with X/Do in the region of low Reynolds number in which $-\alpha_u$ has a large value. In latter case, $\ln U_m$ is not proportional to $\ln X$. On the other hand, since $X_0 = XU_m/\bar{W}_0$ at $\alpha_u = -1$, then

$$\frac{X_0}{Do} = \left(\frac{Rb}{c_u Ro} \right) \quad (17)$$

According to Fig. 5, the numerical value of c_u is nearly equal to 0.052 in the region of high Reynolds number. The slope of the line seems to approach to 1 as shown in Fig. 20 by the dotted line in the region of $Rb > 500$. Since the dotted line gives $Rb/Ro = 1/13$, the numerical value of X_0/Do is nearly equal to 1.5 according to Eq. (17). Fig. 21 shows the experimental relations for the relation between X_0/Do and Rb .

5.2 Comparison among the distributions of velocity, temperature and concentration

It may be considered that the change in the thickness of velocity boundary layer $L_{\frac{1}{2},u}$ with the condition at the nozzle exit is caused by the change in inner

Fig. 21 Relation between X_0/Do and Rb .

layer thickness $B_{0,u}$. The theoretical value of the boundary layer thickness on the wall ⁽⁸⁾ is given by

$$B_{0,u} = 3 \left(\frac{\nu X}{U_m} \right)^{0.5} \quad (18)$$

The values obtained by substituting the above-mentioned empirical relation into Eq. (18) are plotted against Ro in Fig. 22 in the dimensionless form of $B_{0,u}/X$, which shows a good agreement with b_u .

Although the thickness of temperature boundary layer $L_{\frac{1}{2},t}$ also varies with the exit flow condition of jet, it is caused by the variation of outer layer in this

Fig. 22 Comparison of calculated inner boundary layer thickness and b_u .

case. Since the thickness of thermal boundary layer at the wall is determined by the heat transfer, $B_{0,t}$ hardly changes when the wall temperature is fixed at a constant.

The position of the maximum concentration in any section of X lies on the surface of the plate, and the thickness of concentration boundary layer $B_{\frac{1}{2},c}$ varies with the exit condition of jet just as in the cases of velocity and temperature.

Fig. 23 shows a comparison of these distributions with nearly equal Reynolds number. It is obvious from this figure that temperature and concentration distributions are hardly different each other in their outer layer regions, that is, in the regions further than the positions where the values are halves of the maxima.

Fig. 23 Comparison of velocity, temperature and concentration distributions.

6. Conclusions

Followings are drawn as the conclusions of this experiment.

(1) In the impinging jet on a flat plate, the flow along the plate is laminar within the range of the exit Reynolds number less than 2,000, and is turbulent more than 2,000.

(2) The distances from the wall to the maximum and half points of properties along X are proportional to X , and the linear equations passing through the impinging center are assumable.

(3) The velocity distributions for air jet with and without temperature differences from surrounding air and for carbon-dioxide gas jet show almost the same profiles for the same exit Reynolds number.

(4) $B_{1/2,A}$ is larger than $B_{1/2,u}$ and $B_{1/2,t}$. And $B_{0,t}$ depends on the heat transfer driven by the temperature difference between the plate surface and the issuing gas.

(5) The empirical equations for decay of T_m and A_m along X are given in rather simple forms, while the decay of U_m shows a complicated form because of the effect of boundary layer at the plate surface.

(6) The spatial distribution of velocity fluctuation lies almost flat throughout the flow.

(7) It is shown that the mixing length obtained from the measurements of velocity fluctuation is proportional to X , its values are independent of the exit flow conditions, and that the mixing length of impinging jet has the same values as that of free jet.

(8) Eddy viscosity of impinging jet is much larger than that of free jet.

(9) Entrainment of surrounding air by the jet is larger than that of free jet, and agrees well with Hertel's quasi-empirical equation.

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