Dust-proof Characteristics of a Bypass Flow Type Flowmeter Using a Hot Wire*

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Abstract

The authors experimentally examined dust deposits on a hot wire when employed as an air flowmeter. The following points were considered: surface temperature, hot wire diameter, air flow velocity, inertial separation effect, and collision ratio of dust particles onto the hot wire in a dust-proof type flowmeter. The last two points were evaluated using simulations based on experiments and theoretical calculations. As a result, it was found that the output change due to dust deposits on the hot wire could be prevented using a bypass flow type flowmeter, in which the inertial separation effect was taken into consideration.

Key Words : Flow Meter, Dust, Bypass Passage, Hot Wire, Impaction Efficiency

1. Introduction

Flowmeters employing a hot wire are used to determine fluid flow by measuring heat transfer and heat transition. These instruments are characterized by high response. In long term use, however, the hot wire output changes due to a change in the radiation quantity, if dust in the fluid has deposited onto the wire. In this paper, the authors experimentally examined the dust-proof characteristics of a bypass flow type flowmeter having a structure in which the hot wire is arranged inside the bypass passage. Points considered include the surface temperature of the hot wire and inertial separation of dust at the bypass passage inlet.

2. Nomenclature

- t : Time
 V_0, V : Hot wire outputs before and after dust deposits
 D_p : Diameter of dust particles
 U_0 : Air flow velocity at the bypass passage inlet, around the cylinder
 U : Air flow velocity around the hot wire
 X_b : Collision ratio of dust particles in a bent tube
 Y_b : Transmittance ratio of dust particles in a bent tube
 X_s : Collision ratio of dust particles against cylinder
 r_1, r_2 : Radii of hot wire before and after dust deposits

- Δr : Thickness of dust layer
 Q_0, Q : Radiation quantities from the hot wire before and after dust deposits
 ℓ : Hot wire length
 θ_a, θ_s : Temperatures of air and hot wire
 h_1, h_2 : Heat transfer coefficients before and after dust deposits
 λ_0, λ : Thermal conductivities of air and dust layer
 Re : Reynolds number
 Nu : Nusselt number
 ρ, ρ_a : Densities of dust particles and air
 CD : Resistance coefficient of sphere
 x, y : Distances

Fig.1 Outline of experimental device

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V_y : Air flow velocity in "y" direction
 ζ : Vorticity
 ϕ : Stream function
 u, v : Air flow velocities

3. Experimental Device and Method

Fig. 1 outlines the experimental device. Dust was quantitatively supplied from the top of the device by slightly vibrating a metallic ball by means of the vibrator. The equipment was constructed in such a way that moisture, produced by an atomizer, and oil steam, warmed by a heater, could be supplied at the same time. In order to confirm that the air flow remained unchanged during experiments, a Venturi tube was used in the upstream and negative pressure was measured by a pressure sensor.

In this device, a metallic bar (brass) combined with several thermocouples was heated at one end to provide a range of temperatures in the testpiece. A flowmeter was mounted with hot wire probes in the main and bypass passages. These passages were designed to be easily removable. One was used to examine the effect of the surface temperature on the dust deposits, while the other was used to measure changes in hot wire output due to dust, as well as to examine the inertial separation effect of dust.

Fig. 2 shows the surface temperature measuring positions of a heated bar. Thermocouples were embedded 0.5 mm from the upper edge of the bar at intervals of 10 mm.

Fig. 3 shows the shapes of the two tested bypass passages. In model A, the inlet of the bypass passage was open in the direction parallel to the main passage, while in B, it was open in the direction

Fig. 2 Surface temperature measuring positions of the heated bar

Fig. 3 Shapes of tested bypass passages

perpendicular to the main passage. Hot wire probes were mounted inside both the main and bypass passages in each model, and the output change of the hot wire was measured.

Fig. 4 shows four inlet shapes of the bypass passage in model B. Each arrangement allowed inertial separation of dust particles at the bypass passage inlet. Model B-4 was designed such that the air flow introduced into the bypass passage collided against a flat plate after passing through a circular nozzle (φ8 mm).

Fig. 5 shows the structure of the hot wire probe employed for the tests. The hot wire (φ0.5 mm) was attached to support bars (φ1.0 mm) via lead wires (φ0.2 mm). Accordingly, the lead wires as well as the hot wire could serve as the radiator.

4. Experimental Results

4.1 Dust deposit conditions

In order to examine the effect of hot wire surface temperature on the dust deposits, experiments were done using the heating bar (see Fig. 2) as the testpiece. The dust used consisted mainly of SiO₂ (75 - 63%) and had a particle size of 5 - 10 μm (90%) (JIS Z 8901-1974). Figs. 6 and 7

Fig. 4 Shapes of inlets of tested bypass passage in Model B (circled area of Fig. 3)

Fig. 5 Structure of hot wire probe

show experimental results.

Fig. 6 shows dust deposits, photographed from the top, after detaching the testpiece from the experimental equipment. No coating was used on the heating bar surface. In Fig. 6 (a), dust and water were supplied at the same time, while in (b), dust and oil were. No dust deposits were seen above the boundary where the surface temperature was the same as the boiling point of the liquid used (water : 100°C, Oil : 200 - 230°C), but deposits were seen at lower temperatures. This indicated that dust adhesion was mainly due to the liquid being present on the heating bar surface. When the surface temperature was higher than the boiling point, no dust deposits were seen because of the absence of water and oil components.

Fig. 7 evaluates the ratio B/D_0 (where B = the dust deposit width and D_0 = the heating bar diameter) as a function of surface temperature, with and without coatings as a parameter. In Fig. 7(a) no coating was applied and B/D_0 changed abruptly near the boiling point of water. On the other hand, the B/D_0 ratio changed gradually for oil, because its boiling point was a temperature range due to the presence of several components. From these results, dust deposits due to moisture in the open air could be prevented by setting the hot wire temperature above 100°C. If liquid components having a boiling temperature higher than the hot wire temperature are contained in the air, it is difficult to prevent dust deposits by the surface temperature effect. From these experimental results, it is clear that dust deposits are absent if no liquid component is present on the solid surface to cause adhesion of particles.

The authors attempted to remove liquid component adhesion by using a hydrophobic or oil-phobic coating material. Fig. 7(b) shows the results when the heating bar was coated with fluorine coating material A, while Fig. 7 (c) shows those when the heating bar was coated with silicone resin coating material B. In both cases, dust deposits were seen at a higher temperature as than with the results without a coating, but their formation was not

prevented. Figs. 8 and 9 plot B/D_0 versus wire diameter and air flow velocity, respectively, when dust is supplied to an unheated hot wire probe. The B/D_0 ratio decreased as the wire diameter D_0 was increased or the air flow velocity U was decreased. Thus, it was advantageous to use a large diameter hot wire to avoid dust deposits.

4.2 Change in hot wire output due to dust deposits

Fig. 10 shows experimental results about changes in output of the hot wire (mounted in the main passage) with time when dust was supplied at the rate of 3.0 g/h. In these experiments, neither water nor oil was added to the dust. After the experiments, the hot wire probe was observed with a microscope. Since the hot wire was heated above 100°C, dust deposits due to moisture in the open air could be prevented, and the hot wire was found to be free of dust deposits.

In the arrangement shown in Fig. 5, dust deposits were seen because of the low temperature of the lead wire and support, causing the hot wire output to be low. The dust deposits increased here as the air flow velocity U decreased. When $U = 6.6$ m/s, the hot wire output temporarily recovered in about 13 and 25 minutes because the deposited dust was exfoliated by the air stream; this represented the saturated condition of the deposit. Judging from the fact that almost all changes in V/V_0 occurred in the first 10 minutes, and V/V_0 remained almost unchanged thereafter, the output dropped about 1% only so long as no dust was deposited on the hot wire, even if it was employed for a long time.

Fig. 11 plots V/V_0 at $t = 30$ min, for a changing air flow velocity; V/V_0 dropped noticeably as U decreased. In order to

Fig. 6 Surface temperature and dust deposit conditions (after 20 minutes)

Fig. 7 Relation between surface temperature and B/D_0

examine the cause, the power consumption was compared with that of the hot wire probe by using a $\phi 50 \mu\text{m}$ platinum wire instead of a lead wire and support in the hot wire probe shown in Fig. 5. When the platinum wire was employed, the power consumption was reduced by 23% at $U = 6.6 \text{ m/s}$ or by 11.3% at $U = 24 \text{ m/s}$ as compared with the hot wire probe. When U was smaller, the heat radiation from the lead wire increased, causing its effect on the output to increase and also causing the effect of increase when the dust deposit was seen on the lead wire and support. Accordingly, the output drop due to dust deposit would be prevented by suppressing the heat radiation from the lead wire and support by

Fig.8 Relation between B/D_0 and wire diameter D_0

Fig.9 Relation between B/D_0 and air flow velocity U

Fig.10 Change in hot wire output due to dust deposits

reducing the diameter of these components or some such similar means.

Fig. 12 shows changes in V/V_0 when a turbulence bar (5 mm in diameter) was placed horizontally at a position separated from the hot wire by 50 mm in the upstream direction. When there was a turbulence in the air stream, the dust deposit decreased, and the V/V_0 drop decreased.

Next, the authors simulated a change in the radiation quantity with calculations, assuming that the hot wire was contaminated with dust deposit. Dust was apt to be deposited on the upstream of the hot wire; it did not deposit easily on the entire circumference as shown in Fig. 7. In order to keep track of the qualitative change in radiation quantity in dust deposited areas, change of the radiation quantity was calculated when the dust deposited evenly on the entire circumference of the hot wire as shown in Fig. 13. Radiation quantities Q_0 and Q before and after dust deposits are defined by ;

$$Q_0 = h_1 \cdot (\theta_s - \theta_a) \cdot 2\pi r_1 \ell \dots\dots\dots(1)$$

$$Q = \frac{2\pi \ell \cdot (\theta_s - \theta_a)}{\frac{1}{h_2 r_2} + \frac{1}{\lambda} \ln\left(\frac{r_2}{r_1}\right)} \dots\dots\dots(2)$$

Fig.11 Relation between hot wire output change V/V_0 and air flow velocity U

Fig.12 Effect of turbulence on V/V_0

Then,

$$\frac{Q}{Q_0} = \frac{1}{\frac{h_1 r_1}{h_2 r_2} + \frac{h_1 r_1}{\lambda} \cdot \ln\left(\frac{r_2}{r_1}\right)} \quad (3)$$

Heat transfer coefficients h_1 , h_2 were obtained by substituting $r = r_1, r_2$ into the following equation, respectively.

$$Nu = 2hr/\lambda a = 0.32 + 0.43 Re^{0.52} \quad (4)$$

Fig.14 shows calculation results when $r_1 = 0.25$ mm. The parameter $\lambda/h_1 r_1$ was changed by the air flow velocity and thermal conductivity λ of the dust. As the air flow velocity become smaller and λ , larger, this parameter increased. It was possible for Q/Q_0 to become large than 1.0, that is, the radiation quantity increased after dust deposits, rather than before dust deposits. This was because the radiation quantity increased due to an increase in surface area of the hot wire; it occurred when the air flow velocity was low or λ , large. The Q/Q_0 value also became smaller than 1.0 when λ was small because the dust layer showed thermal resistance.

Assume that thermal conductivity λ of the dust remains unchanged. If dust having a small particle size is closely deposited, thermal conductivity λ of the dust layer increases, causing Q/Q_0 to increase. If

Fig.13 Calculation model

Fig.14 Changes in radiation quantity according to thickness, Δr , of dust layer

$\lambda/h_1 r_1$ is 1.1 or 1.2, it changes from a value larger than 1.0 to a value smaller than 1.0 as Δr increases. This tendency can appear depending on the air flow velocity and λ . For example, the thermal conductivity λ of soil (dry) is 0.14 (W/m°C). if the air flow velocity is 6.5 m/s, then $\lambda/h_1 r_1$ becomes about 1.2, and Q/Q_0 changes from a value larger than 1.0 to a value smaller than 1.0 as Δr increases.

4.3 Dust-proof characteristics of bypass flow type flowmeter

(1) Change in hot wire output in bypass passage

Fig.15 shows changes in output of the hot wire mounted in the bypass passage when only dust was supplied. In model A, the bypass passage inlet was open in the direction parallel to the main passage, and the same tendency appeared in the output change of the hot wire as that shown in Fig. 10. The effect could not be prevented owing to dust in the structure. Since the bypass passage inlet was a bent tube in model B-2, dust particles collected at the bend. As a result, the output was not reduced much initially. However, the cross sectional area of the passage was soon reduced by the collected dust, causing the hot wire output to decrease. In model B-1, little dust was introduced into the bypass passage, and the cross sectional area of

Fig.15 Change in hot wire output due to dust deposits (effect of bypass passage structure)

Fig.16 Change in hot wire output due to dust deposits (effect of U and λ)

the passage was not significantly reduced. As a result, the hot wire output was basically unchanged.

Fig. 16 shows the results when dust and oil were supplied simultaneously; dust deposits were seen on the hot wire owing to the effect of the oil. When oil was added in model A, the output drop increased even when the air flow velocity remained unchanged, and the effect of the dust deposits on the hot wire appeared. When air flow velocity was small, e.g. $U = 2.7$ m/s in model B-1, the output increased, and then, fell. This was because of the dust layer increased owing to the oil contained in the dust particles. This observation matched the calculations in Fig. 14. As U was increased to 4.8 m/s, V/V_0 was lower than 1.0 at all times, without any hot wire output rise.

Fig. 17 summarizes the effects of all models and of oil on hot wire output. The change in hot wire output was smaller in model B where the bypass passage inlet opened in the direction perpendicular to the main passage than in model A. But in model B-2, the output changed significantly, because the cross sectional area of the tube was reduced. In model B-4, since a circular nozzle was mounted at the bypass passage inlet, the dust particle collection effect increased there, and only particles having small diameters reached the hot wire area, so that the value of the dust layer deposited onto the lead wire and supports increased; thus, the output increased.

(2) Simulation of the inertial separation effect of dust particles

In order to obtain the inertial separation effect of particles in the bent tube shown in Fig. 18, an incompressible flow was assumed, and the potential stream was obtained by the following equation.

$$u = \frac{\partial \phi}{\partial y} \quad (5)$$

$$v = -\frac{\partial \phi}{\partial x} \quad (6)$$

$$\zeta = \frac{\partial u}{\partial y} - \frac{\partial v}{\partial x} \quad (7)$$

Vorticity transport equation

$$\frac{\partial \zeta}{\partial t} + \frac{\partial}{\partial x} (u \zeta) + \frac{\partial}{\partial y} (v \zeta) = \frac{1}{Re} \nabla^2 \zeta \quad (8)$$

Fig.17 Change in hot wire output due to dust deposits

Poisson's equation

$$-\zeta = \nabla^2 \phi \quad (9)$$

Then the trajectory of the particles was obtained by applying the following equation of motion to the stream obtained, assuming that the particles were spherical.

$$\rho \frac{\pi D_p^3}{6} \frac{d^2 y}{dt^2} = CD \frac{1}{2} \rho_a (V_y - \frac{dy}{dt})^2 \frac{\pi D_p^2}{4} + \frac{\pi D_p^3}{6} (\rho - \rho_a) \cdot g \quad (10)$$

For the x direction, the equation was employed with the assumption that the gravity term in the second term on the right side was zero.

Fig. 18 shows the velocity vectors of two bent tubes. Model II indicated the vectors when a trap was used to prevent the sectional area of the tube from being reduced.

Fig. 19 shows the trajectories of the dust particles and the streamlines. Particles sizes were specified as 5 μ m or 10 μ m. The larger particles deviated noticeably from the streamline after passing the bend, and deposited, one-sidedly, in the lower part of the bypass tube. The 5 μ m particles also deviated from the streamline and separated by inertia.

Next, the authors obtained the collision ratio of dust particles against the cylinder using the computational model

Fig.18 Velocity vectors of bent tubes (the vectors at the tube inlets are shown as 1.)

shown in Fig. 20. The particles within width B_b collided against the bottom of the bent tube, and were separated inertially as shown in Fig. 20 (a).

Then, collision ratio X_b was obtained as

$$X_b = \frac{B_b}{D_b} \quad (10)$$

The ratio of particles passing the bend was;

$$Y_b = 1 - X_b \quad (12)$$

The collision ratio X_s against the walls of the cylinder shown in Fig. 20 (b) was represented by the following equation, (assuming that the particles within width B_s collided against the cylinder wall).

$$X_s = \frac{B_s}{D_s} \quad (13)$$

Figs. 21 - 23 show the transmittance

Fig.19 Streamlines and trajectories of dust particles

(a) Bend tube (b) Cylinder

Fig.20 Model for collision ratio

ratio Y_b of the dust particles in the bent tube. As U_0 increased and D_p was larger, transmittance ratio Y_b decreased. Particles with $D_p = 10 \mu\text{m}$ were separated by inertia when U_0 was about 10 m/s. However, particles with $D_p = 5 \mu\text{m}$ could not be separated easily. If the passage of the stream after the bent tube was narrow (e.g. $L_1 = 8 \text{ mm}$ and $L_2 = 4 \text{ mm}$) as shown in Fig. 23, the transmittance ratio Y_b decreased as compared with other cases, while the inertial separation effect was large.

Fig. 24 shows the collision ratio X_s against the walls of the cylinder. X_s increased as the particle size D_p became larger and the air flow velocity U_0 became higher. Calculations were made assuming that the wire size D_s of the hot wire was 0.5 mm. For D_s smaller than 0.5 mm, X_s increased; this caused more dust deposits. The tendencies shown in Figs. 8 and 9 coincided with those of the collision ratio X_s .

Fig. 25 shows the relation between $Y_b \cdot X_s$ and U_0 when the hot wire is put in

Fig.21 Relation between Y_b and U_0 in the bent tubes ($L_1, L_2 = 8 \text{ mm}$)

Fig.22 Relation between Y_b and U_0 in the bent tubes ($L_1 = 4 \text{ mm}, L_2 = 8 \text{ mm}$)

Fig.23 Relation between Y_b and U_0 in the bent tubes ($L_1 = 8 \text{ mm}, L_2 = 4 \text{ mm}$)

the after-stream of the bent tube as shown in Fig. 20 (a); hence it represents the collision ratio of dust particles against the hot wire in the bypass passage. When setting $L_2 = 4$ mm, $Y_b \cdot X_s$ was less than 0.4, and the inertial separation effect increased.

Fig. 26 shows the inertial separation effect in the cylindrical nozzle of model B-4 (Fig. 4). The sizes were based on experiments by Wong and Ranz.²⁾ If U_0 was smaller than its value at $Y_b = 0.1$, Y_b was larger than 0.1 and the inertial separation effect decreased. But if U_0 was larger than its value at $Y_b = 0.1$, Y_b was smaller than 0.1 and the inertial separation

effect increased. For example, in model B-4, $L_2 = 3$ mm, $D_p = 5 \mu\text{m}$ and if air flow velocity $U = 2.7$ m/s (in this case, $Y_b > 0.1$), the hot wire output changed. If air flow velocity $U = 6.6$ m/s (in this case $Y_b < 0.1$), the hot wire output remained essentially the same. Thus, the effect of dust on the hot wire output can be prevented by optimizing the L_2 size.

5. Conclusions

The dust-proof characteristics of a bypass flow type flowmeter using a hot wire were examined.

- (1) No dust was deposited on the hot wire when the surface temperature of the hot wire was higher than the boiling point of the liquid component contained in the air.
- (2) The dust deposit ratio onto the hot wire increased as the hot wire diameter became smaller and the air flow velocity, higher.
- (3) The dust deposit quantity on the hot wire became saturated at a certain value, and no longer increased. The output change of the hot wire due to the dust deposit became stable at a certain value.
- (4) The dust deposit quantity on the hot wire could be reduced by promoting a turbulence in the air stream.
- (5) If the thermal conductivity of the deposited dust layer was large, the hot wire output could increase owing to the radiation area increase effect, as compared with conditions before deposits formed.
- (6) When the hot wire was arranged in the bypass passage having its inlet opening in the direction perpendicular to the main passage, the dust deposits on the hot wire could be prevented by the inertial separation effect at the inlet, and the drop in hot wire output could be prevented.

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Fig. 24 Relation between X_s and U_0 in cylinder

Fig. 25 Relation between $Y_b \cdot X_s$ and U_0 in a cylinder mounted in the bypass passage

Fig. 26 Inertial separation effect in the cylindrical nozzle