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Characteristics of on-wall in-tube flexible thermal flow sensor under radially asymmetric flow condition

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Abstract

We investigated the ability of an on-wall in-tube flexible thermal flow sensor to measure the flow rate under a radially asymmetric flow condition in a curved tube. The sensor was fabricated on a polyimide film substrate using polymer MEMS technologies. A ring-shaped sensing structure was formed by mounting the sensor on the inner-wall surface of a straight tube that follows a curved tube. The sensor characteristics were experimentally evaluated by varying the distance L from the end of the curved tube, the curvature angle θ, and the curvature radius r of the curved tube. The output signals from the sensor were the same when the distance L was over 5 mm at various curvature angles and curvature radiuses. The sensor is thus well suited for measuring the flow rate in spiral tubes.

Keywords: Flow sensor; Thermal sensor; Flexible sensor; Polyimide film; Radially asymmetric flow condition

1. Introduction

Flow-rate detection is important in industrial fields and laboratorial studies, and various types of the flow sensor structures have been developed to satisfy their measurement requirements. The gas tube is frequently used as the curved configuration to decrease the occupied volume in such applications as compact heat exchangers (Fig. 1). In this case, the velocity distribution of the gas flow becomes asymmetric in the radial direction, as shown in Fig. 1.

Two different types of thermal sensors are commonly used to detect the gas flow rate in the tube. One is on-wall out-of-tube heater sensing [1–4], and another is hot wire sensing [5–21]. In the case of the on-wall out-of-tube type sensor, the heating and sensing elements are winded up outside the tube, and the flow rate inside the tube is measured by detecting the change of the electrical resistance of the sensing element (Fig. 1(a)). This type is not sensitive to the velocity distribution of the gas flow in the circumferential direction, and therefore is able to output the stable value under the asymmetric velocity distribution. This is because the winded round heater averages the circumferentially nonuniform velocity distribution. However, the sensor has the following drawbacks because it detects the flow rate inside the tube through the tube wall.

(1) Dependence on tube properties.
The measured value largely depends on the tube properties, such as tube material and wall thickness. The sensor basically needs the metal as the tube materials to reduce the thermal resistance of the tube during heat transfer.
(2) Large response time and high power consumption.
The metal tube has a large heat capacity, and therefore the sensor requires a large response time and power consumption. It is difficult to detect precisely the transient variation of flow rate.

The hot wire type made by MEMS technologies is able to overcome these problems, because of its small heat capacity and high thermal isolation from the tube. The small-sized sensing element is conventionally placed at the center of the tube to

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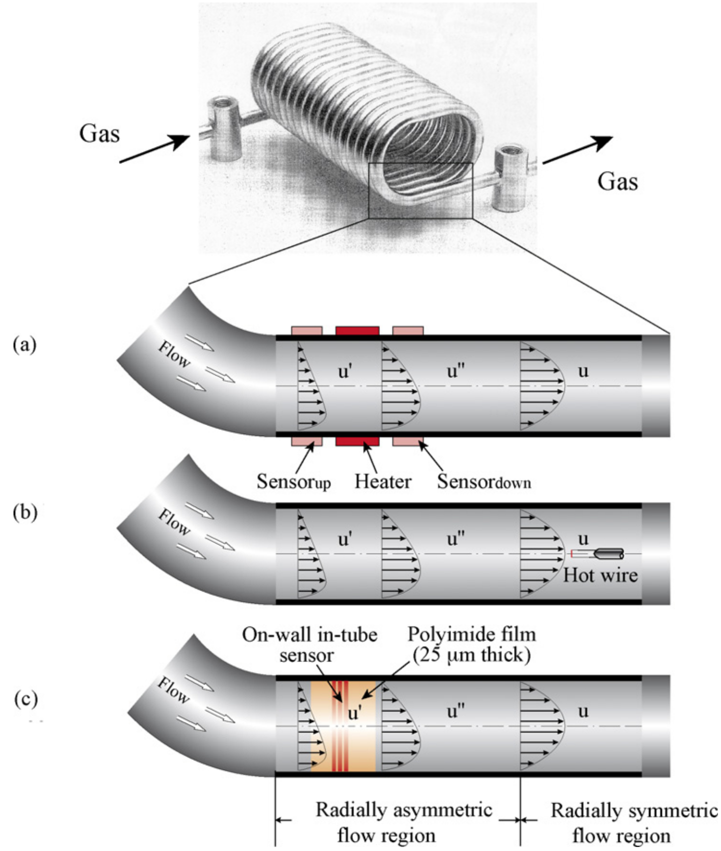

Fig. 1. Conceptual diagrams of hydraulic flow condition: (a) on-wall out-tube sensor arrangement, (b) hot wire arrangement and (c) on-wall in-tube sensor arrangement in entry region of curved tube.

realize the high thermal isolation, and it detects the gas velocity at a point in the center of the tube (Fig. 1(b)). The sensor is therefore not able to output the constant value when the velocity distribution is asymmetric in the radial direction. This type is difficult to be used in the measurement in the curved tube application, in which the velocity distribution changes depending on the curvature radius and angle of the tube and on the distance from the exit of the curved part to the sensor position (Table 1).

The aim of this paper is to provide a novel type of on-wall in-tube thermal flow sensor for the flow-rate measurement in a curved tube.

2. Operation principle

Schematic view of the on-wall in-tube flexible thermal flow sensor is shown in Figs. 1(c) and 2. The sensor consists of a ring-shaped heater element, which works as a flow-rate sensing,

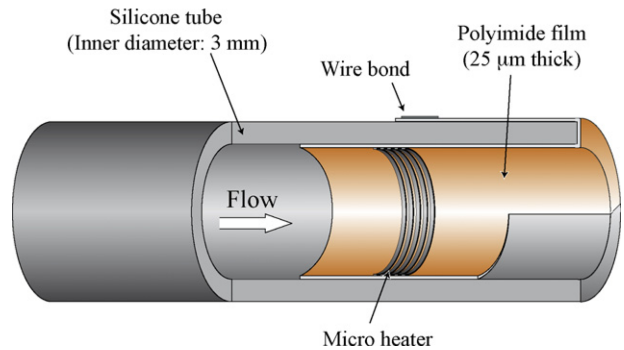

Fig. 2. Schematic cross-sectional view of on-wall in-tube flexible thermal flow sensor.

on a flexible polyimide film that has a low thermal conductivity. The sensor is fabricated on a polyimide film substrate and then mounted on the inner-wall surface of the tube to form the ring-shaped sensor structure. The fabrication process and assembly method are described in more detail in Section 3.

2.1. Flow-rate detection

The ring-shaped sensing element detects the flow velocity near the inner wall of the tube. The mechanism of flow-rate detection under asymmetric flow in the radial direction is as follows. The ring-shaped sensing structure averages the circumferentially nonuniform velocity distribution in a distorted flow condition. This means the sensor output is independent of the radially asymmetric characteristics of the velocity distribution. The sensor thus outputs a constant value against the corresponding flow rate even if the velocity distribution is not attained to the axisymmetric condition, i.e., fully developed condition. The sensor also has the following advantages because the sensing heater element is thermally isolated to the tube by the polyimide film.

(1) The sensor output does not depend on the tube material and wall thickness.
(2) The sensor is able to precisely detect the change of the flow rate with a short response time, because of high thermal isolation and small heat capacity of the heater. It also drastically reduces the power consumption.

2.2. Heat transfer

The amount of heat transferred from the heater element placed in the tube to the surrounding medium can be broken down into thermal convection, thermal conduction, and thermal

Table 1
Comparison among different types of flow sensors

	Independent of tube properties (material, wall thickness)	Small response time and low power consumption	Output stable value under asymmetric velocity distribution in tube
(a) On-wall out-tube sensor	×	×	○
(b) Hot wire	○	○	×
(c) On-wall in-tube sensor	○	○	○