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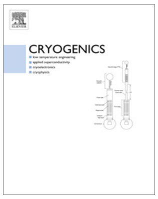

A new method for flow measurement in cryogenic systems

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ABSTRACT

A new method for mass flow measurement of fluids in pipes is presented; its novelty lies in the capability for intrinsic calibration. The method is founded on a concept, where two independent analytic expressions for the flow rate are formed from the same direct measurement readings (input parameters). If the input parameters were error-free, the two expressions would yield identical results, by definition. This fact can be used as goal function in a minimization routine that removes systematic errors of the inherently error-prone input parameters. The uncertainty of the mass flow measurement is then only influenced by statistical effects and is typically less than 1% with regard to the measured value. The new method is explained by a proof-of-principle that is based on measurements in a large-scale cryogenic system. The intrinsic calibrations can be executed in situ at any moment during operation of a plant, and with no need for a reference standard. While the new method is applicable in any system involving single-phase fluid flow, it offers particular advantages in cryogenic application.

1. Introduction

Flow measurement is a standard task in any technical application involving fluid flow. A large variety of methods is known for the measurement of gas flow in pipes, such as differential pressure, vortex, ultrasonic, Coriolis and thermal flow measurement. In *thermal* or *caloric* mass flow meters, heat is added in heating elements and heat transfer functions to the fluid are evaluated. The traditional two-element principle shown in Fig. 1 comprises two consecutive elements in flow direction, which are electrically heated and cooled by the fluid through the conductive wall. An element may consist of a platinum wire, to which an electrical current is applied for heating and where the voltage drop is evaluated for temperature measurement at the same time. If both elements are heated with the same heat load $\dot{Q}$ while the fluid is stagnant, the temperature profile in the tube wall is symmetric with regard to the median between the elements, and the temperature difference ΔT between the elements is theoretically zero (dotted line in Fig. 1). In case of fluid flow, the temperature profile is shifted in flow direction and a temperature difference $\Delta T \neq 0$ can be measured that is proportional to the mass flow rate (full line).

In such thermal systems, the correlation between the temperature difference ΔT and the mass flow rate $\dot{m}$ is complex. It is influenced by design (i.e. distance between elements, tube size, materials and shape of heat exchangers – affecting axial and radial thermal resistances, as well as contact resistances), by flow and fluid parameters (i.e. viscosity, conductivity, specific heat), by sensor orientation and by surrounding conditions. A large number of design solutions[1] is known that aim for the minimization of error effects and usually for linear sensor characteristics. The functional correlation $\dot{m} = f(\Delta T)$, however, can only be determined by multi-point calibration and stored in form of sensor-specific curve coefficients. The latter generally holds for all other measuring principles, all involving models with empiric components that must be determined by calibration in test stands under reference conditions.

Apart from a solution [1], no flow meter for cryogenic application can be found as serial product on the market today, mainly because a manufacturer calibration with low-temperature helium or hydrogen is rather unfeasible in terms of cost and effort. In this paper, a new method for flow measurement is presented, with the ability for *intrinsic* calibration that can be executed during operation of a cryogenic installation. The intrinsic calibration is founded on a new concept, whereby two independent analytic expressions for the flow rate are formed from the same measurement readings (input parameters). If the input parameters were error-free, the two expressions would yield identical results, by definition. This fact can be used as goal function in a minimization routine that removes systematic errors from the inherently error-prone input parameters. The standard uncertainty of the flow rate is then only

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[1] In the three-element principle, for instance, the heating and temperature measurement functions are separated.

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Nomenclature

A	reference surface of the heat exchanger
A_W	inner tube surface
$\dot{C}$	capacitance flow
c_p	specific heat capacity of the fluid
d	inner tube diameter
F_i	systematic error of parameter i
k	overall heat transfer coefficient w.r.t. A
L	heat exchanger length
$\tilde{L}$	dimensionless length parameter
$\dot{m}$	mass flow rate
Nu	Nusselt number
Pr	Prandtl number
$\dot{Q}$	heat flow
R	thermal resistance of the heat exchanger
R_C	contact resistance
R_V	virtual resistance
R_α	convective resistance
R_λ	conductive resistance
Re	Reynolds number
T_A	temperature of the heat exchanger surface A
T'_F	fluid inlet temperature
T''_F	fluid outlet temperature
ΔT	temperature difference
$\Delta T'$	inlet temperature difference
$\Delta T''$	outlet temperature difference
ΔT_m	logarithmic mean temperature difference
ΔT_{sat}	saturation temperature shift
u	standard uncertainty
w	fluid velocity
α	convective heat transfer coefficient
η	fluid bulk viscosity
η_w	fluid viscosity at wall temperature

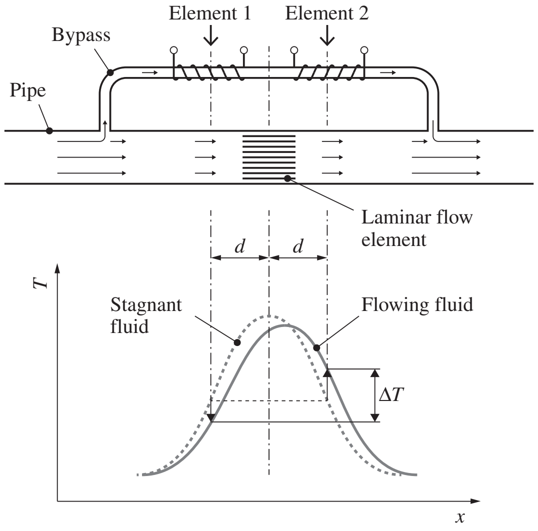

Fig. 1. Measuring principle of thermal flow meters.

influenced by random errors and is typically $u_{\dot{m}} < 1\%$ with regard to the measured value.[2]

The new method is introduced in Section 2 with the aim of first presenting a *global* picture of the underlying model. For the sake of clarity, no details are discussed at this point on how the model conditions can be implemented. The method's feasibility is proven in the subsequent Section 3 on the basis of experimental data. Two options for transient flow measurement are presented in Section 4, as the intrinsic calibration requires quasi-static flow conditions. Design features and peculiarities of operation are then discussed in Section 5, explaining *why* this method works even under practical conditions that deviate to some extend from the analytic model. Conclusions are drawn in the final Section 6 together with an outlook for future activities.

2. The new measuring method

2.1. General layout and expressions

The new method proposed in this paper is a *thermal* method, yet it is fundamentally different from all thermal flow measuring principles known so far.[3] The new method is based on the general layout of fluid flow through a heat exchanger as illustrated in Fig. 2. The heat exchanger is heated with a controllable heat load $\dot{Q}$ and is designed in such a way that the surface temperature T_A is nearly constant in flow direction z. Upstream and downstream of the heat exchanger, the fluid inlet and outlet temperatures T'_F and T''_F are measured, respectively. In contrast to classical thermal flow meters, T'_F and T''_F are installed in such distances from the heat exchanger, where:

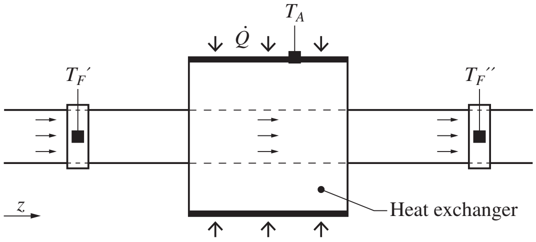

Fig. 2. General principle of the sensor design.

- radial temperature profiles in the fluid are negligible,
- the temperature rise in the tube wall by axial heat conduction from the heat exchanger is negligible, and
- no requirements on the symmetry of T'_F and T''_F with regard to the heat exchanger exist.

The measurement readings of $\dot{Q}, T_A, T'_F$ and T''_F can be reduced to three measuring quantities, expressing the temperature measurements in form of inlet and outlet temperature differences $\Delta T'$ and $\Delta T''$ as shown in Fig. 3.

With the three quantities $\dot{Q}, \Delta T'$ and $\Delta T''$, two analytic expressions can be formed. The first expression is the energy balance of the fluid flow[4]

$$\dot{Q} = \dot{m}\, c_p (\Delta T' - \Delta T'') \qquad (1)$$

where c_p is the specific heat capacity of the fluid. The second expression is given by kinetics in the heat exchanger

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[2] The uncertainty of commercial flow meters is usually given in percent of the *measurement range*.

[3] Common features in all thermal methods are the required knowledge of the fluid's specific heat capacity c_p and the restriction to single-phase flow.

[4] The constant surface temperature T_A cancels out in (1), hence $(\Delta T' - \Delta T'') = (T''_F - T'_F)$.