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Transferability of insertion flowmeter calibration to customer-specific applications

How can a t-mass insertion flowmeter calibrated up to a maximum flow of 10 300 kg/h be used to service an application with a maximum flow range greater than this?

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Summary
The sensing element of thermal mass flowmeters is very small in relation to the cross-sectional pipe area of the corresponding measuring system. As a result, the sensor delivers a “point” flow measurement – known as specific mass velocity [kg/(s · m^2)] –, rather than an averaged mass velocity. This specific mass velocity is assumed to be representative of the measurement velocity at all points in the cross-sectional area of the pipe. By multiplying the measured specific mass velocity with the cross-sectional area of the pipe’s inner diameter, the mass flow can be derived. Important for this solution is to find the insertion depth for the sensor that corresponds to a point within the pipe that is (for all pipe sizes and flow rates) as close to the average mass velocity as possible. Because the sensor can measure the specific mass flux, and as long as this remains within the calibrated range, scaling of the flow rate with respect to varying pipe diameters is not a problem. Simply stated, two prerequisites for flow scaling must be met: Firstly, the sensor has to be placed in a position within the pipe, where it delivers the average specific mass velocity and secondly it has to be insured that the maximum calibrated specific mass velocity is not exceeded.

Basis for calibration
t-mass insertion devices are calibrated using air on a traceable, accredited rig in a DN 175/7" (177.75 mm) tube under stable conditions and with a turbulent, fully developed flow profile. The conditioned air flow through this rig reaches a maximum velocity of 100 m/s (328 ft/s), which corresponds to the maximum calibrated range. This maximum expressed in mass flow follows:

$$A \cdot \rho \cdot u = 0.025\, m^2 \cdot 1.173\, \frac{kg}{m^3} \cdot 100\, \frac{m}{s} = 2.91\, \frac{kg}{s} \cdot 3600\, \frac{s}{h} = 10500\, \frac{kg}{h}$$

A Cross-sectional area calibration tube [m^2]
ρ Density of air at reference conditions [kg/m^3]
u Flow velocity [m/s]

The basis for this calibration is to establish a relationship between the power coefficient (the measured power input to the sensor divided by the measured temperature differential [$\text{Temperature}_{(\text{heater})}$ – $\text{Temperature}_{(\text{fluid})}$]) and the mass flow, which is derived from the corresponding sensor's Reynolds number. The sensor's Reynolds number can be determined during the calibration for each primary calibration point and set in relationship to its corresponding power coefficient. In the end, an average velocity is calibrated into the sensor at the point of measurement for each primary calibration point. This velocity – or more correctly, "specific mass flow" – is referred to as ρ · u and is measured in $kg/(s \cdot m^2)$.

In this case, because it is the Reynolds number (Re) at the point of measurement that is being assessed during the calibration, it is this calculated Reynolds number of the sensor that is of importance. This does not correspond with the calculated Reynolds number of the pipe, but is rather derived from the following:

$$Re = \frac{\rho \cdot u \cdot d}{\mu}$$

ρ Density
u Velocity
d Characteristic length
μ Dynamic viscosity

The "characteristic length" (d) is the diameter of the heated sensor that houses the temperature element. This corresponds to approximately 2 mm (0.079"). Using this length, the density and viscosity of air at reference conditions and the maximum velocity reached by the calibration rig, a Reynolds number of ca. 12 700 is obtained.

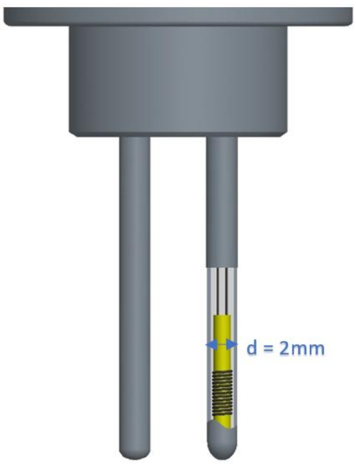

Figure 1: Cut-away of heated sensor sheath and view of temperature element (d = characteristic length).

In the end, it is ρ · u that we are seeking, as this provides us with the specific mass flow expressed in $kg/(s \cdot m^2)$. Thus, knowing the sensor's Reynolds number for a specific power coefficient allows us to determine ρ · u and consequently the mass flow because all other variables, i.e. viscosity and pipe diameter, are known. Following is the Reynolds equation rearranged according to ρ · u:

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$$\rho \cdot u = \frac{Re \cdot \mu}{d} \cdot A = \frac{12700 \cdot 0.0185 \frac{kg}{m \cdot s}}{0.002\, m} = 117.3 \frac{kg}{m^2 \cdot s}$$

A Cross-sectional area of DN 175/7" tube (diameter = 177.75 mm)
μ Dynamic viscosity of air at reference conditions (0.0185 kg/m · s)

This is the specific mass flow for the calibrated limit at a single point in the pipe (the point of measurement at the sensor tip). Now, by multiplying this specific mass flow with the area of the corresponding cross-sectional pipe area, we arrive at the mass flow in kg/s:

$$117.3 \frac{kg}{m^2 \cdot s} \cdot 0.0248\, m^2 = 2.91 \frac{kg}{s} \quad \text{or} \quad 117.3 \frac{kg}{m^2 \cdot s} \cdot 0.0248\, m^2 \cdot 3600 \frac{s}{h} = 10500 \frac{kg}{h}$$

Customer-specific applications
Assuming now that the customer's application is air at 1 bar(a) and 24 °C (75 °F) with a flow velocity of 100 m/s (328 ft/s) through a pipe DN 350 (14"), by doing the same calculation, we arrive at a maximum mass flow value almost 400% higher than that of the calibrated maximum flow using air:

$$A \cdot \rho \cdot u = 0.096\, m^2 \cdot 1.173 \frac{kg}{m^3} \cdot 100 \frac{m}{s} = 8.39 \frac{kg}{s} \cdot 3600 \frac{s}{h} = 40630 \frac{kg}{h}$$

A Cross-sectional area customer pipe [m^2]
ρ Density at reference conditions [kg/m^3]
u Flow velocity [m/s]

Therefore, essentially what is important for sizing the application within the calibrated range of the device is to make sure that the maximum calibrated specific mass flow (ρ · u) is not exceeded. Then, by multiplying this specific mass flow with the cross-sectional area of the customer's pipe, the corresponding maximum calibrated range of the customer's application is attained. As we just saw, this application-specific calibrated maximum can be much higher than the actual calibrated maximum.

Finding the average pipe velocity
Another important consideration for establishing a reliable basis for calibration – and consequently, a reliable transferability to other pipe sizes – is to ensure that the calibrated point velocity (or specific mass flow) corresponds with the *average* mass flow velocity in the pipe. The thermal mass flow principle relies on a basic assumption about the flow profile when "inferring" the mass flow, i.e. the flow profile is well-developed as it would or should be in a calibration rig, for example. Furthermore, the point of measurement in the pipe (the depth at which the sensor tip, which houses the heater, is inserted within the tube) must correspond with the average flow velocity in the pipe – obviously, even in a well-developed flow profile, not every radial position within the pipe will experience the same flow velocity. The reason for this measurement prerequisite is that the point velocity (specific mass flow) is multiplied by the cross-sectional area to attain the mass flow rate. This assumes, of course, that the measured point velocity is the same at every other point along the entire cross-sectional area of the pipe. As it is not, it must be determined – usually through experimentation – at which point in the pipe the average velocity is most accurately represented.

Depending on the pipe size, however, this optimal point of measurement may differ. Usually in the case of inline devices, the position of the average flow velocity is determined for each nominal diameter and the sensor position optimized for each of these. In the case of insertion devices, however, in which the actual pipe diameter is unknown and a determination of the average flow velocity for every possible pipe diameter within the entire application range (DN 80/3" to DN 1500/60") is unrealistic, an attempt is made to determine an optimal measurement position which applies equally well to all possible pipe diameters. For t-mass insertion devices, this empirically determined optimum is at 0.3 × DN (DN = nominal diameter). Every t-mass insertion device is calibrated at this position. Therefore, to achieve the best possible results, it is imperative that t-mass insertion devices are always installed to this same depth in the customer-specific pipe.

The relationship of the specific mass flux to the location in a pipe has been investigated at great length by Endress+Hauser Flow and determined to be 0.3 × DN. Below is a graph depicting the results of such an investigation. In the graph on the right, we see a correlation of the specific mass flux for three different nominal pipe diameters (DN 80/3", DN 100/4" and DN 150/6") when the sensor is inserted to 0.3 × DN. The specific mass flux for each of these pipe sizes at varying flow rates is almost identical. This correlation between the same specific mass flows in different pipe sizes provides the basis for scaling the mass flow from the calibration to customer applications. In the graph on the left, we see the flow rates as they correspond to the power coefficients for the different pipe sizes. All of these measured flows were within the specified accuracy of t-mass.

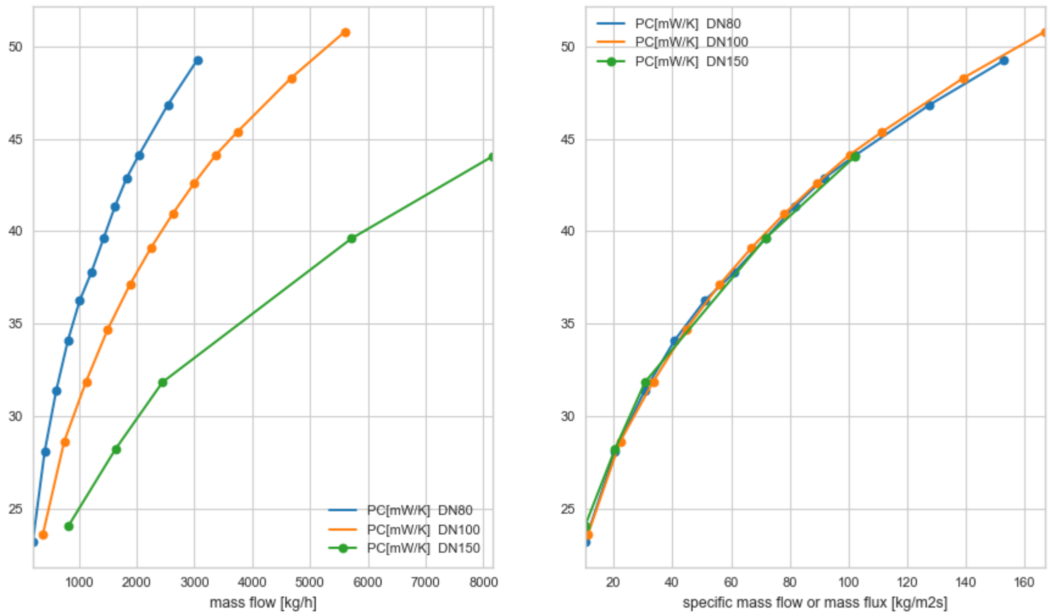

Figure 2: The graph on the right shows the relationship of the power coefficient (y-axis) to the specific mass flow (x-axis) in three different pipe sizes (DN 80/3", DN 100/4" and DN 150/6"). The specific mass flow ($\rho \cdot u$) is for all three pipe sizes identical. The graph on the left shows the relationship of the power coefficient (y-axis) to the mass flow (x-axis) for the same three pipe sizes. The mass flow is the specific mass flow multiplied with the cross-sectional area of the inner pipe diameter ($A \cdot \rho \cdot u$).

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Conclusion

As we can see, the transferability of an insertion flowmeter calibration to a customer application having a different pipe diameter to that of the calibration rig, and consequently different flow rates, are both theoretically and experimentally provable. The basis for a reliable transferability is a solid calibration and good installation practice. As long as the specific mass flux of the calibration is not exceeded, the sensor's positioning in the pipe is in accordance with the required 0.3 × DN, and the installation follows Endress+Hauser Flow's recommendations, the transferability is a given.