

A FULLY OPTIMISED THERMAL MASS FLOW INSTRUMENT WITH THE HELP OF BIG-DATA

EL-FLOW® Prestige, June 2017



| WHITE PAPER |

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Introduction

The trend of big-data in today's digitization of everything has also affected the world of flow measurement. The amount and speed of data transmission continues to increase, and digital flow meters are employed in an even wider range of applications.

This white paper describes the ins and outs of influential factors which impact the accuracy, stability, linearity and pressure correction of a state of the art mass flow meter. A mass flow meter based on the bypass principle with 'smart intelligence' on board to control the flow meter and providing a high level of reproducibility using big-data.

Conclusion

A holistic view on a mass flow meter makes it possible to design components which offer optimal performance both as individual components and within the whole flow meter/controller system. This study resulted in a fully optimized thermal mass flow system.

Data on the pressure drop curve form the basis to reduce the sensitivity for tolerances. After years of gathering data and gaining experience about the differential temperature balancing principle (DTB) it was possible to optimize the flow sensor and the gas flow linear across a wider range to reduce the sensitiveness for tolerances.

By adding an additional temperature sensor and an integrated database with gas properties, full control on the output could be realized. The temperature sensor is being used to select corresponding gas properties which are on-board to adjust measurement values for environmental influences, resulting in an accurate conversion factor.

Gas flow measurement in general

Flow measurement is recognised as one of the 'need-to-know' process parameters, alongside temperature, pressure and level measurement. Accurate mass flow measurement of gases is critical in operations and control of many industrial and laboratory processes. In the food and beverage sector, the chemical industry and semiconductor fabrication, flow meters accuracy is often the determining factor between optimum quality and rejected products. In areas like laboratory research, pilot plants and custody transfer, precise and repeatable measurement is equally critical. In other applications high levels of accuracy may not be so crucial and flow meters are used to give an indication of the rate at which a gas is flowing through a pipeline.

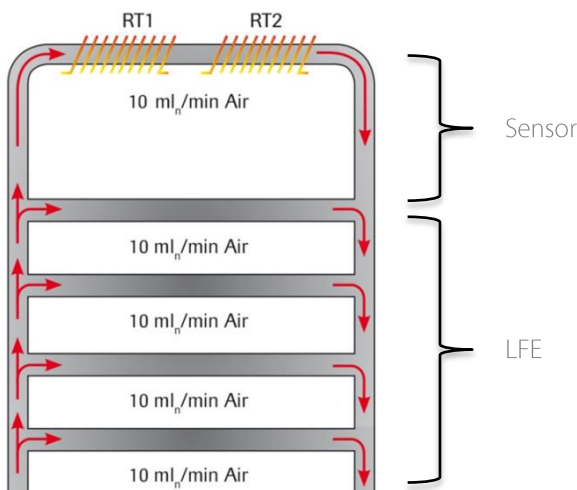
Thermal mass flow meters

Thermal mass flow meters measure the mass flow of gases, employing a combination of heated elements and temperature sensors, with thermodynamic principles used to derive actual flow. They do not require correction for changes in gas-temperature, pressure or density and are extremely accurate, especially when measuring low and very low flow rates, and are no longer regarded as high cost.

However, mass flow is often expressed in volumetric units and the mass is converted to volume under provided conditions. Because of the influence of the Heat Capacity (C_p) and the Thermal Conductivity (λ) where the conversion factor is derived from, changes in pressure and density do have an impact.

Thermal mass flow meters are often limited to clean gas; however, with the 'non-bypass' principle, there are no narrow pipelines to clog with particulate, and they, therefore, can handle most gases. *1

In this white paper we will focus on, the thermal mass flow meter using the bypass principle. In this configuration, the mass flow is measured in a bypass of the main flow channel - instead of the channel itself (picture 1), also known as the 'shunt' principle of the Laminar Flow Element (LFE). In electronics, a shunt is a device which allows electric current to pass around another point in the circuit by creating a low resistance path. Thin plates which are used to create the LFE allows the measurement of very small (less than 1 mln/min) as well as medium (20 ln/min) flow rates. The bypass is a capillary tube with an internal diameter of 0.2mm, and this small size allows for fast response times and low energy requirements, as only a small tube volume needs to be heated.



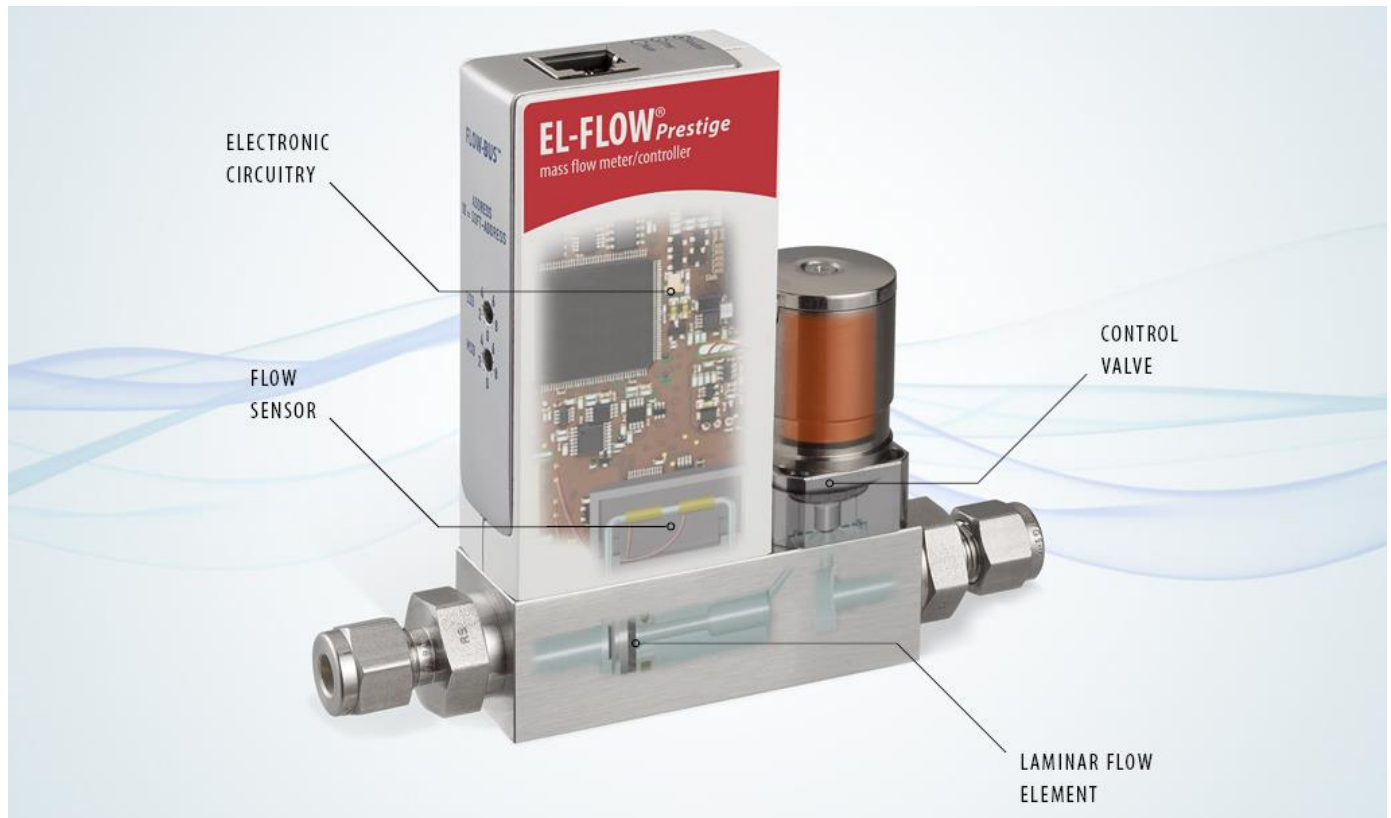
[Picture 1: Shunt principle of the Laminar Flow Element (LFE)]

Only part of the gas flow will flow through the sensor. The rest flow will flow through the LFE.

Gas flow measurement & control at universities and R&D institutes

Especially in the research environment, progressive insights are part of the game: tomorrow's approach might be completely different from today's. A gas supply device with many configuration possibilities is advantageous. 'Many' may refer to a large range of gases and process conditions that have to be handled, but also to a broad way of communicating with the device, i.e. the input/output (I/O) possibilities. Last but definitely not least - inside as well as outside the research environment - is the need for low cost of ownership of such a gas supplying device.

Let's dig deeper into these devices, to see what technology is responsible for measuring and controlling this gas flow rate in tomorrow's application in an accurate and stable way. Here we take the Bronkhorst EL-FLOW Prestige series thermal mass flow meters and controllers as an example (as shown in picture 2).



[Picture 2: Artist impression of EL-FLOW® Prestige Mass Flow Controller]

A thermal mass flow meter essentially consists of a gas inlet and outlet port, a gas flow measurement part, and measurement, control & communications electronics. With the addition of a valve that controls the desired gas quantity, the mass flow meter operates as a mass flow controller. Insights about the working principle can also be found in the following Youtube video.

Link: <https://www.youtube.com/watch?v=IMkkXo1KkxA>

Most mass flow controllers are designed for and calibrated with a specific type of gas and at a specific gas flow rate. The further away from this designed 'working point', the less accurate the device will be performing.

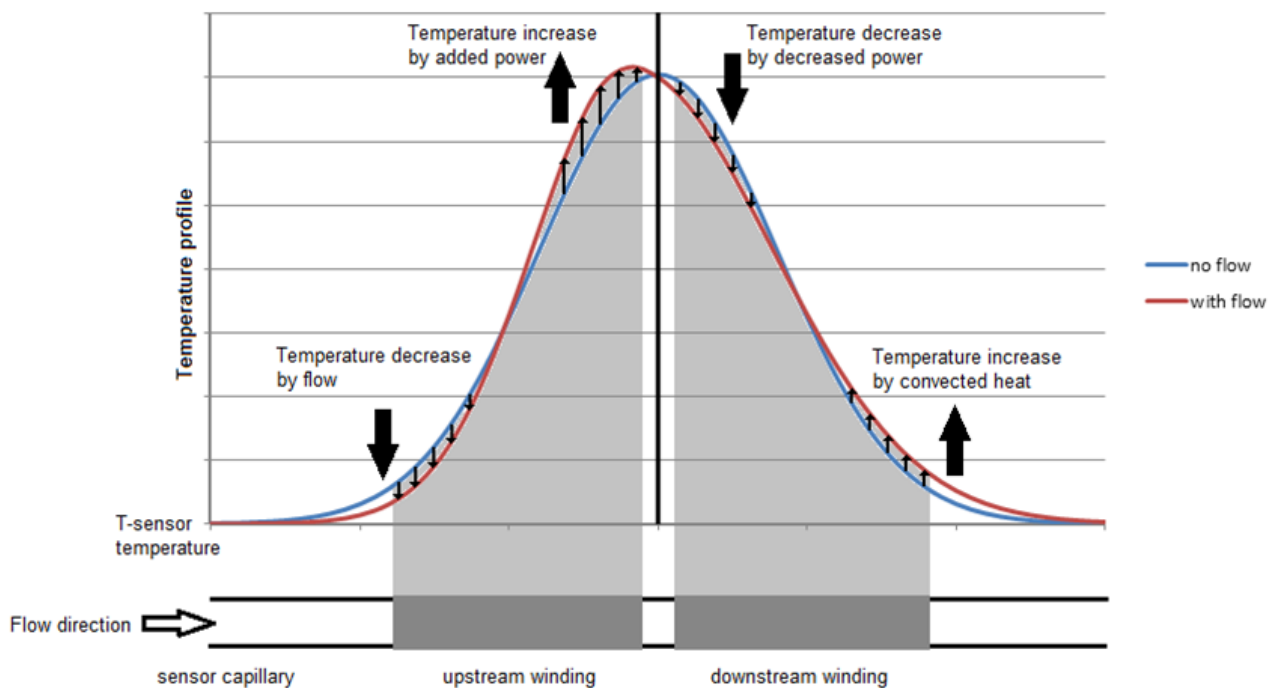
Laminar flow element (LFE)

The laminar flow element is a component which consists of thin plates with very shallow channels, converting turbulent gas flow at the device inlet into a laminar flow. In this regime with a low Reynolds number (<100), the pressure drop is proportional to the (volume) flow rate of the gas. The resistance of the laminar flow element determines the proportion of flow between the bypass sensor and the main flow channel, and hence the portion of the flow that is fed to the sensor. The ability to operate in this low-flow regime with good control and accuracy is responsible for the high turndown ratio of the device with a value of 1:150 - the ratio between the minimum and maximum flow, so an indication of the measurement range.

Flow sensor based on Differential Temperature Balancing (DTB)

The thermal mass flow sensor consists of a thin capillary tube fitted with two combined windings for heating and temperature measurement, and an additional temperature sensor for sensor stability. The two windings are electrically powered to warm up the tube above ambient temperature. As long as there is no gas flow, the power required to warm up the windings evenly is equal for both windings, resulting in a zero value measured by the flow sensor.

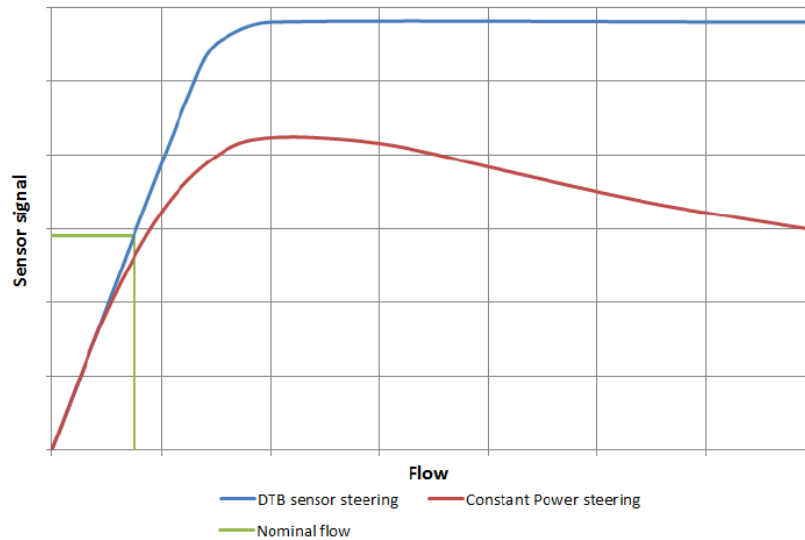
When gas is flowing, the resistance of the laminar flow element ensures that a small proportional portion of the flow is fed to the sensor. This cold gas cools the first sensor winding. In order to maintain a constant average temperature over the first winding, the power to this winding is increased to provide additional heat. The second winding sees that the gas has been warmed up, so the power to the second winding is decreased to maintain a constant average temperature over this winding. The power difference between the two windings is a direct measure for the mass flow - which is the Differential Temperature Balancing (DTB) principle, as shown in picture 3.



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[Picture 3: Differential Temperature Balancing (DTB) temperature profile of EL-FLOW® Prestige mass flow instrument]

To obtain the best performance, the flow sensor should have a linear relation between the sensor signal and the gas flow rate in the process window under consideration. To this extent, second-order effects had to be minimised, which has been established by preventing the windings from cooling down by keeping them at the same temperature.



[Picture 4: Flow sensor signal as a function of gas flow]

In picture 4 the flow sensor signal as a function of gas flow has been displayed from the EL-FLOW Prestige mass flow meter. Both the upstream- and downstream windings in the sensor are power regulated to T_{amb} of 35°C. The difference in power between the windings is a measurement for the flow.

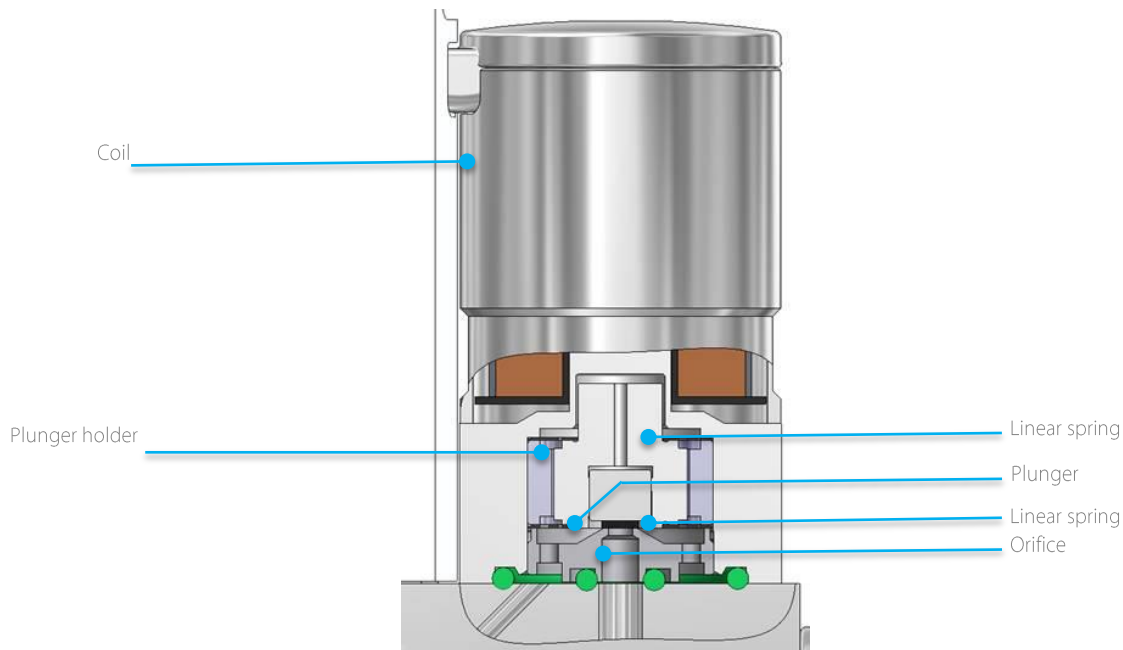
The Differential Temperature Balancing (DTB) sensor steering in a calorimetric flow regime provides a better linearity. The DTB sensor signal does not drop when purging or exceeding the maximum flow, thus resulting in an accurate flow.

An additional temperature sensor in the EL-FLOW Prestige is being used to select corresponding gas properties which are on-board, such as density and heat capacity, and to adjust measurement values for environmental influences, for long-term sensor stability. In turn, stability and reproducibility are directly related to process yield.

A *positive* side effect of the attempts to make the relation between the flow sensor and the gas flow linear and less sensitive for tolerances, is a reduced deviation between devices.

Machine builders who have to build hundreds of machines will benefit. If one device is defect, they are easily interchangeable; it will not be necessary to fine-tune the entire machine, reducing downtime of the facility during maintenance.

Linear behaviour of the control valve



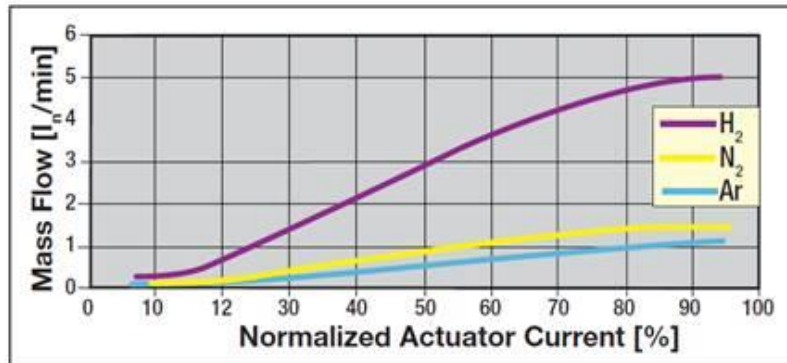
[Picture 5: Top mount valve]

The control valve of the thermal mass flow controller, as shown in picture 5, consists of a plunger surrounded by an electromagnetic coil. This electromagnetic coil exerts a force on the magnetic plunger holder; this force is in balance with the linear springs that normally keep the control valve closed. As the plunger comes free of the orifice, the result is a gas flow through the device. The signal from the flow sensor is compared with the set point in the electronics of the device. The electric current of the coil is adjusted so that the distance between the plunger and the orifice is exactly right for controlling the desired quantity of gas.

Suspension of the construction inside the electromagnetic coil by a double linear spring gives a smooth and frictionless control, in such a way that leak tightness and smooth opening of the valve are well balanced. Moreover, the long life span of the valve means less frequent replacements.

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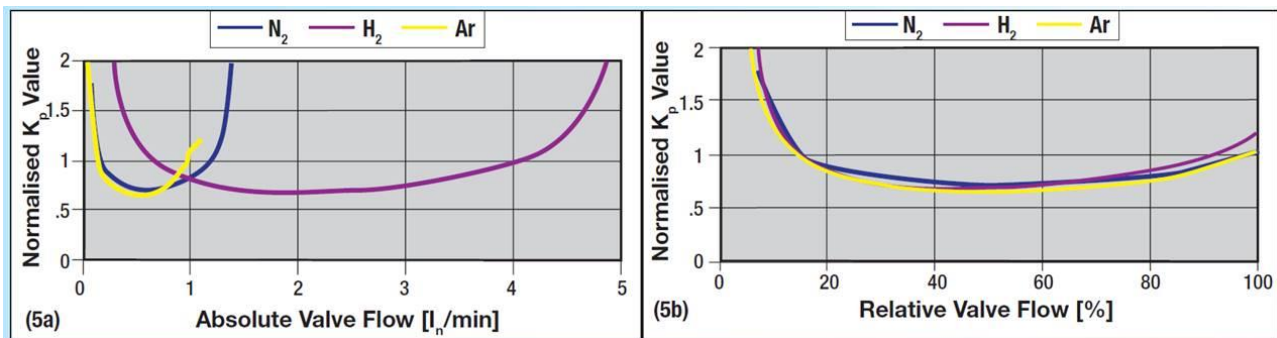
For the best performance, the correlation between the electric current of the coil and the distance between plunger and orifice - and hence the relation between current and gas flow - should be as linear as possible. A redesigned magnetic flux path in combination with a tuning model that accurately predicts the behaviour of the non-linear transfer function (coil current vs. distance between plunger and orifice) is used to adjust the influence of the valve non-linearity on the controller response.



[Picture 6: Example: Typical transfer function of an electromagnetically actuated control valve. By optimisation of the electromagnetically flux path, the S-shape (H_2) has become more linear.]

As seen in picture 6, the amount of mass flow going through the valve differs quite a lot for different gases. However, the stroke of the valve is always the same. Or in other words: the relative amount of gas going through the orifice, compared to the maximum amount that can go through, is always the same. Therefore it makes sense to compare not the *actual* flow, but the *relative* valve flow for different conditions, such as gas type, temperature and pressure.

As seen in picture 6 and 7a, the shapes of the curve show common features, and when scaled to the maximum valve flow, the curves actually coincide as shown in picture 7b. The shape of this single curve is characteristic for a valve, and by compensating with the inverse curve we end up with a linear curve, that makes the control valve reproducible in speed and leads to a response time that is independent of pressure, temperature or gas type.



[Picture 7a and 7b: Example: Optimum controller gain settings for nitrogen, hydrogen and argon as a function of (a) absolute and (b) relative valve flow]

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The elastomer seal material of the plunger is subject to swelling when temperature increases. Reducing the amount of elastomer also reduces the temperature effect, resulting in a robust PID controller that is independent of temperature, which is applicable for a temperature range of -10...+70°C for which the EL-FLOW Prestige can be applied.

Furthermore, traditional elastomer seal materials have a disadvantageous characteristic that, in case of long lasting closing periods of the valve, they deform somewhat around the seat. When the valve is opened subsequently, the elastomer remains stuck to the seat for a short period of time. For a controller it is hard to deal with this 'dead time', and the instant detachment of the seal results in an overshoot. Applying a non-stick coating to the seal has solved this problem.

This is especially interesting for applications with a repeating open-close pattern, for dosing small amounts of gas after which the valve closes again. Without sticking effect, there is no dispersion in the open time resulting in a good reproducibility.

Most gases are well compatible with the (default) Viton, EPDM or Kalrez seals. However, a few gases have a deteriorating effect on the sealing material, which may swell or vanish to some extent.

Embedded models & algorithms

A model has been developed that predicts the behaviour of the flow sensor combined with the pressure drop vs. flow behaviour of the laminar flow element. Due to this calculation model, calibration with only one single reference gas is sufficient to characterise a multi-gas/multi-range mass flow meter for both its entire flow range (multi-range) and all other process gases to be used (multi-gas). This approach allows for serving a large range of different gases and process conditions with only a small number of devices - also saving on materials and storage - and results in low operational and maintenance costs.

As an example the EL-FLOW Prestige is able to calculate the physical properties of 25 commonly used gases using actual temperature and pressure and is able to use this data to calculate the mass flow for different gases or mixtures based on the stored calibration. The advantage of having many gas properties on board is the ability to use the same device for other, new applications. By using Bronkhorst FlowTune software the device can be configured for new gas types - for example for another pressure - all on a parametric basis, which makes the device more versatile. A PLC can help you select the on-board curves.

A drawback of the multi-gas/multi-range approach with one device is that versatility goes at the expense of accuracy, especially far away from the designed working point. Scaling to flows much higher than the working point will result in inaccuracies due to spreading in conversion, whereas scaling to very low flows will result in a sensitivity to zero point errors. With the EL-FLOW Prestige this phenomenon is still present, however, due to the linear behaviour of its components, this effect is significantly smaller. This means that scaling is possible to a larger range with an adequate accuracy compared to traditional mass flow controllers.

The device as such

With the EL-FLOW Prestige mass flow meter, changes in specifications or small adjustments are possible on-site (for gas, pressure, temperature, flow and advanced input/out operations). Physical cable connection is right on top or at the side of the device. Downtime is reduced during operation, as there is no need to remove the device from electrical or physical system connections.

Beneath the metal cover of this mass flow instrument are the basic digital PC board electronics, with functions for measurement and control, and an optional interface board for fieldbus connection and user selectable input/output options. Smart 'intelligence on board' handles the gas conversion, corrected for temperature and pressure, and assures optimum accuracy.

The versatility of the device is also demonstrated by the many input/output options that can be selected and adapted afterwards. Currently, a choice can be made out of 10 possible configurations, including obvious analogue signal options, RS-232 or fieldbus communication.

Additionally, a programmable pin at the 9-pin sub-D connector is available for customized I/O configurations. This also opens opportunities for users who would like to apply the mass flow controller for flow measuring and simultaneously controlling a shut-off valve or a pump.

The mass flow instrument can be used together with pressure sensors in order to make them more stable, and also to be able to measure large ranges of 100 to 1 bar. For certain gases, the signal strongly changes as a function of pressure. Without adjusting for this, the mass flow measurement or control is not accurate.

Indeed, features of thermal mass flow meters and controllers such as immunity to fluctuations in inlet conditions, low flow accuracy, the ability to use multiple gases and mixtures in one device and configurable I/O options will improve the process yield for e.g. R&D environments, while reducing cost of ownership.

[For more information about the EL-FLOW Prestige Gas mass flow meters and controllers, please see our brochure](#)

**1 An example of a non-bypass thermal mass flow meter/controller is the Bronkhorst MASS-STREAM series.*