A method of flow measurement based on the reaction force. Reaction flowmeters

H. M. Moțit
Control and Instrumentation Association of Romania
hmotit@aair.org.ro, Bucuresti, Romania

Abstract
It is presented a worldwide new flow measuement method and the configurations of the first types of „reaction flowmeters" (both without and with moving parts) achieved thereof, both elaborated by the author. Also a global analysis of the functional equations and of the experimental and theoretical calibration of the reaction flowmeters without moving parts it is provided.

1. Preliminary considerations

Both this worldwide new flow measuement method and the different types of the configurated flowmeters achieved thereof, are the subject matter of the patent application filed, with European Patent Office, EP 19020006.3.
The author named this method „Reaction force method of flow measurement" and the related flowmeters „Reaction flowmeters".
These new types of flowmeters (both without and with moving parts) have been configurated as a result of the first practical use of the „Unitary Synthesis and Design Method of Flowmeters", recently elaborated by the author and of the developments from [1] .

2. The principle of the method

The principle of this new method consists in the measurement of the fluid mass flow rate Q_m by putting in evidence the reaction force $F_R = F_R(Q_m)$ of the measured fluid, which is proportional to Q_m, and the measurement of its different effects. The reaction force F_R is generated by a common basic specific configuration, developed for the fluid flow path through flowmeter. The force F_R is exerted by fluid on the wall of this specific configuration, and is measured, directly or indirectly, by the measurement of its derived effects (torque, differential pressure, force, frequency), proportional with F_R, according to the analytical dependence of F_R on Q_m .

3. Reaction flowmeters classification

Following the principle of "the reaction force method of flow measurement" the common basic configuration of the fluid flow path through reaction flowmeter (named "the reaction measurement system") has been developed for all types of reaction flowmeters, and consists of a pair of two distinct functional parts: the inlet tube and the reaction element (reaction tube or reaction drum).
The "reaction measurement system" ensures the input of the measured fluid into the flowmeter through the inlet tube, which is an immobile and rigid tube to flowmeter housing, for all types of reaction flowmeters and then the fluid is transferred by a coupling to the reaction element.
The reaction element (reaction tube or reaction drum) performs by its specific configuration, two mandatory requirements, of the reaction flowmeters namely, on the one hand to get the maximum effect of the reaction force $F_R(Q_m)$ exerted by the measured fluid on the reaction element and, on the other hand, to ensure the constructive facility that this effect of reaction force F_R be measured with precision.
Because the operating mode of the reaction flowmeters is determined by the operation of their measuring system, it results the following classification of the reaction flowmeters:
- *Reaction flowmeters without moving parts.*
The reaction element is practically immobile, during the measurement, and it is usually achieved by a reaction tube.
- *Reaction flowmeters with moving parts.*
The reaction element is mobile during the measurement, and it is achieved by a reaction tube, or by a reaction drum in an evolved variant.
The reaction flowmeters in each above group have different coupling configuration, correlated with relative positions between inlet/outlet flowmeter connections (horizontal collinear axis, vertical collinear axis, perpendicular axis).
Further both groups of the reaction flowmeters are successively presented.

4. Reaction flowmeters without moving parts

4.1 Common reaction measurement system.
In Figure 1 is presented the basic configuration of "the reaction measurement system", common for all reaction flowmeters without moving parts.

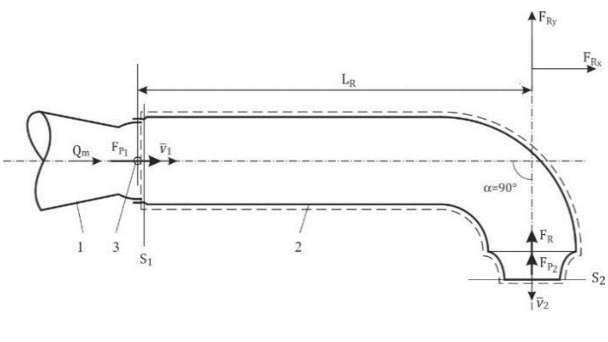

Figure 1: Configuration and the operating principle of the reaction measurement system

The reaction measurement system consists of the pair of immobile inlet tubes 1, configured as a extension of inlet connection of flowmeter, and the reaction tube 2.
Following the both mandatory requirements, mentioned in Section 3, the reaction tube 2 is specifically configured, on the one hand bent at 90^0 at its outlet end, the fluid discharge end, (to solve the first requirement), and on the other hand, is provided at the its inlet with a shaft 3, perpendicular on it, which ensures a potential rotation mobility of the tube around the shaft (to solve the second requirement).
So configured, the reaction tube of the reaction flowmeters without moving parts ensures the possibility to detect and to measure the moment M_R of the reaction

force F_R to its rotation shaft, and by its processing to be calculated the mass flow rate Q_m.

4.1.1 Functional equations

4.1.1.1 Reaction force equation

The analysis is related to the reference control volume, marked with interrupted line in Figure 1, with faces at the inlet (section S1), which is the outlet from connection 1,with inner area A1, and at the outlet (section S2) with inner area A2 of the reaction tube 2, encompassing the reaction tube walls.

According to the momentum theorem, the rate of change of momentum through the control volume, for a fluid which has a steady flow in a non-uniform flowing in a stream tube, is the total force exerted on the fluid and has the vector equation:

$$Q_m \times (\bar{v}_2 - \bar{v}_1) = \bar{F}_{RT} + \bar{F}_P + \bar{F}_G \qquad (1)$$

where:

Q_m - mass flow rate of fluid

$\bar{v}_1$ - inlet velocity of fluid into the control volume, (the outlet velocity from the connection 1)

$\bar{v}_2$ - outlet velocity of fluid from the reaction tube

$\bar{F}_{RT}$ - force exerted on the fluid by the reaction tube, touching the control volume

$\bar{F}_G$ - force exerted on the fluid body (e.g. fluid weight of control volume)

$\bar{F}_P$ - force exerted on the fluid by fluid pressure outside the control volume

$\bar{F}_P = \bar{F}_{P1} + \bar{F}_{P2}$

$\bar{F}_{P1}$ - force exerted on the fluid at the inlet of the control volume

$\bar{F}_{P2}$ - force exerted on the fluid at the outlet of the control volume

According to Newton's 3rd Law, regarding the "Principle of Action and Reaction", the force exerted by the fluid on the solid body (e.g. reaction tube), touching the control volume is opposite to $\bar{F}_{RT}$ force, with the reaction force $\bar{F}_R$.

So the reaction force is given by expression:

$\bar{F}_R = -\bar{F}_{RT}$, and has the vector equation:

$$F_R = Q_m \times (\bar{v}_1 - \bar{v}_2) + \bar{F}_{P1} + \bar{F}_{P2} + \bar{F}_G \qquad (2)$$

Because the reaction tube shown in Figure 1 is placed in horizontal plane (a two dimensional *x*, *y* reference system), it is normally to use, instead of $\bar{F}_R$ vector equation, its corresponding scalar equations, respectively its components $\bar{F}_{Rx}$ (in *x* - direction) and $\bar{F}_{Ry}$ (in *y* - direction).

It is convenient to choose the co-ordinate axis so that one is pointing in the direction of inlet velocity.

So in Figure 1the *x* - axis points in the direction of the inlet velocity $\bar{v}_1$, and as a consequence the *y* - axis points in the direction of the outlet velocity $\bar{v}_2$.

On the one hand, the only fluid body force is that exerted by gravity, which acts into the paper plane, a direction that is not relevant in this analysis (for all types of reaction flowmeters that are horizontally placed).

On the other hand, it is known from continuity that $Q_V = A_1 \times v_1 = A_2 \times v_2$,

Generally it is calculated the resultant reaction force $F_{R_{resultant}}$ by combining its components, F_{Rx} and F_{Ry}.

Specifically for reaction tube from Figure 1 it is observed that the component F_{Rx}, of reaction force in the *x* - direction, does not contribute to the displacement of the reaction tube, because its effect is integrally take over by the rotation shaft 3, which ensures the mobility of the tube for any its potential rotation.

Following these considerations, respectively by using the Bernoulli equation, and by replacing v_1 and v_2, for the control volume which is open at both its ends, it results:

$$F_{R_y} = Q_m^2 \times k_1 \times \rho^{-1} \qquad (3)$$

where:

ρ - density of the measured fluid

$k_1 = 1/A_2 + 0{,}5 \times (A_2/A_1^2 - 1/A_2)$- constructive constant

4.1.1.2. Flow rate equations

A. Flow rate equation of the reaction flowmeter with the measurement of reaction torque.

This equation is deduced and with reference to the Figure 2, which presents the configuration of this basic type of the reaction flowmeters without moving parts.

The moment of the reaction force F_R, which tends to rotate the reaction tube 2 about its shaft 3, is named the reaction moment M_R and has the equation:

$$M_R = F_{R_y} \times L_R \qquad (4)$$

where: L_R –moment arm

The reaction moment M_R is permanently balanced by the torque τ of the torque sensor, according to equation:

$$M_R = \tau \qquad (5)$$

Remark:

$\tau = \theta \times C$, where C is the coefficient of torsional rigidity, and θ is the torsion angle, with an insignificant maximum value of only $0{,}2^0 \dots 0{,}8^0$.

Consequently this type of reaction flowmeter is basically considered a flowmeter without moving parts.

By replacement of F_{R_y} in M_R expression, from previous equation (3), it results:

$$Q_m^2 \times \left[\frac{1}{A_2} + \frac{1}{2} \times (\frac{A_2}{A_1^2} - \frac{1}{A_2})\right] \times \rho^{-1} \times L_R = \tau \qquad (6)$$

Respectively:

$$Q_m = (\rho \times \tau \times k_1^{-1} \times L_R^{-1})^{1/2} \qquad (7)$$

B. Flow rate equation of the reaction flowmeter with the differential measurement of pushing (reaction) pressure.

This equation is deduced and with reference to the second configuration of reaction flowmeters, related to Figure 3, that ensures, proportionally to the component F_{R_y} of reaction force F_R, the force F_S which pushes, by a pin, on a face of a separation membrane, with pushing (reaction) pressure p_s. This pressure has the expression:

$$p_S = F_S/A_m = F_{R_y} \times L_R/(L_S \times A_m) \qquad (8)$$

where:

L_R - arm of moment M_R

L_S - arm of force F_S moment

A_m - active area of separation membrane

According to flowmeter configuration, on the same face of the separation membrane acts simultaneously with F_S, the static pressure p_f of measured fluid with the equivalent force $F_f = p_f \times A_m$

So the opposite face of the membrane (respectively the transmissions liquid) takes over the total pressure $p_S + p_f = (F_S + F_f)/A_m$, that is the result of the action of these two forces.

A differential pressure sensor measures the difference $\Delta p = p_s$ between these pressures $(p_s + p_f)$ and p_f

that acts on its (+) and (-) inlets.
By processing of the previous p_s expression, it results:

$$F_{R_y} = \Delta p \times L_S \times A_m / L_R \quad (9)$$

By replacing in equation (9) of F_{R_y} from equation (3) and by processing is obtained the measured mass flow rate equation:

$$Q_m = (\rho \times \Delta p \times k_2)^{1/2} \quad (10)$$

where:
$k_2 = L_S \times A_m \times L_R^{-1} \times k_1^{-1}$ - constructive constant

4.2 Basic configurations of reaction flowmeters

The connection of these flowmeters to the related pipe can be achieved in two ways (mostly with horizontal collinear inlet/outlet connections or in some cases with inlet/outlet connections with perpendicular axis).

With reference to their specific measurement systems, two configurations of reaction flowmeter are presented further.

A first embodiment is the reaction flowmeter with the direct measurement of the reaction torque, in the fluid (Figures 2a, b).

The measuring fluid enters the flowmeter through the inlet connection 1 and continues to flow through the reaction tube 2, by passing through the spherical coupling made of a nozzle (bumped head) 3 belonging to the inlet connection 1 and a nozzle (bumped head) 4 of the reaction tube.

The reaction tube is bent at the other end by 90^0, and terminates with a convergent nozzle. The fluid exiting the reaction tube is taken up by a suitable convergent nozzle of the outlet connection 5 through which it is discharged from the flowmeter, and so is not disturbed the evacuation of the fluid from reaction tube.

Connections 1 and 5 are fixed rigidly and tightly to the housing 6 of the flowmeter, having their symmetry axes collinear, on the same horizontal line.

The radial equidistance between the nozzles (bumped heads) 3 and 4 is constructively achieved by two small bosses 7 of the bumped head 4 of the reaction tube, placed vertically, up and down around the vertical shaft 8, and so it is ensured an insignificant contact friction between the nozzles 3 and 4.

Their rigorously concentric positioning is accomplished by a metal shaft 8.

The rigorous positioning of the reaction tube with respect to the inlet connection is ensured by the rigorous concentric positioning of the bumped heads 3 and 4, achieved by rigorous positioning on the same vertical line of the upper bore of the bumped head 3 with the shaft 8. The spatial positioning (*x*, *y*, *z*) between the two bumped heads 3 and 4 is thus rigorously assured, and by threading a nut 9 on the upper outer boss of the reaction tube, is ensured a permanent locking of the shaft 8 in this position.

By means of a wedge 10, the measuring shaft 11 of the torque sensor 12 being rigidly blocked relative to the reaction tube, respectively to its outer boss with which it is provided also at its lower side, fully takes over the torque of the reaction tube.

Correct measurement of the torque is ensured by blocking the rotation of a torque transducer by locking its support shaft 13 relative to the housing of the flowmeter, with a wedge 14 positioned between it and the support 15 which in its turn is rigidly fixed to the housing by screws 16.

The housing of the flowmeter is closed by a cover 17 which screws 19.

The reaction force F_R exerted by the mass flow Q_m at the outlet of the reaction tube, determines the torque $M_R = F_R \times L_R$ which is proportional to flow rate Q_m.

This rotation torque is taken up by the measuring shaft 11 and implicitly by the torque sensor which output signal τ, proportional to Q_m, is taken over by the electronic block 20.

Because the measuring shaft 11 requires a very low torsion angle of $0{,}2^0$ ... $0{,}8^0$ to measure its maximum torque, implicitly, the reaction tube, which is rigid with this shaft, will have the same insignificant rotation angle for the entire flow measurement range ($Q_{m_{min}}$ ... $Q_{m_{max}}$).

So, the rotation angle of the reaction tube being practically insignificant, this type of reaction flowmeter is basically a flowmeter without moving parts.

In the electronic block, on the one hand, is stored, the calibration curve of flowmeter, for the specific nominal operating parameters of measured fluid, and on the other hand, it can provide the polynomial compensation of Q_m with temperature, and pressure, measured by sensors 21 and 22.

Thus, electronic block renders the compensated mass flow rate Q_m with *P* and *T*.

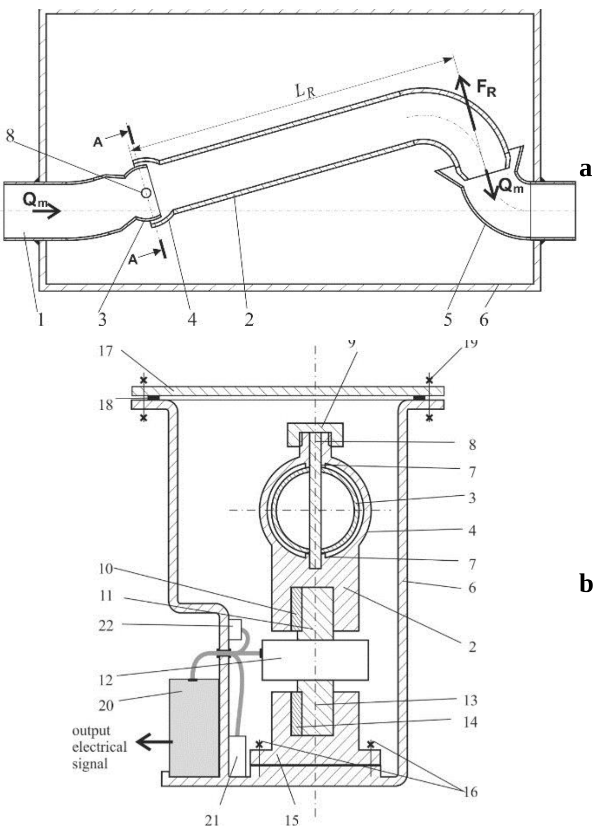

Figure.2 Reaction flowmeter with torque measurement and horizontal collinear connections
a- longitudinal section, b- cross section with a plane A-A

We mention that a similar configuration of reaction flowmeter with the measurement of reaction torque from outside the measured fluid, by magnetic coupling, was also elaborated.

Another type of reaction flowmeter, presented in Figure 3, ensures the measuring of reaction force by the differential measurement of the pushing (reaction) pressure produced by it.

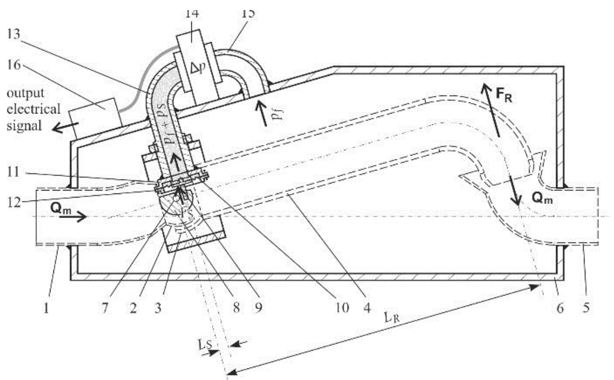

Figure 3. Reaction flowmeter with the measuring of the reaction force by the differential measurement of pushing (reaction) pressure.

The measuring fluid enters the flowmeter through inlet connexion 1 ending with in nozzle (bumped head) 2 which enters a nozzle (bumped head) 3 of the reaction tube 4.
The fluid flows through the reaction tube, which is bent at the other end at $90^{0,}$ and ends with a convergent nozzle and then it is taken up by the outlet connection 5 through which it is discharged from the flowmeter, being provided at its inlet with a suitable converging nozzle in order to be not disturbed the fluid discharge from reaction tube.
Connections 1 and 5 are rigidly and sealed tighten to flowmeter housing 6, being horizontal collinear.
The radial equidistance between the nozzle (bumped head) 2 of the inlet connection and the nozzle (bumped head) 3 of the reaction tube 4 is made up constructively by two bosses, similarly to the solution presented in Figure 2b. The bosses are placed vertically, up and down, around the vertical shaft 7 and, being very small, provide a minimum contact friction between the bumped head 2, of inlet connection 1 and the bumped head 3 of the reaction tube.
The rigorous positioning of the reaction tube relative to the inlet connexion is ensured by the rigorous concentric positioning of the bumped heads 2 and 3, achieved by the vertical shaft.
The rigorous positioning of the shaft 7 in both the horizontal and vertical plane, is accomplished by its passing through two holes placed on the upper and lower walls of the reaction tube support. The centres of the two holes (bearings) being rigorously located on the same vertical axis, it is ensured the insignificant values both for horizontal play and friction of the shaft 7.
The reaction tube 4 is stiffened with the shaft 7 that rests on its support, that is stiffened related to housing 6.
In the boss 8 at a distance L_S from the shaft centre, the pin 9 is rigidly embedded. It remains in permanent contact with the separation membrane 10 to which it permanently transmits the pushing force F_S of the reaction tube 4 as long as fluid flows through it and implicitly is generated by the reaction force F_R.
Since the L_R/L_Sratio is greater than 1, and F_S force is amplified relative to the F_R reaction force.
The pin 9 pushes the separation membrane through a workpiece which directly takes over the F_S force. The membrane takes over the F_S force, and is rigidly tighten and sealed externally between flanges 11 and 12 which are fastened by a screws/ nuts system.
Consequently, on the side towards the fluid, on the separation membrane operates both the static pressure p_f of the fluid and the pushing pressure $p_s = F_S/A_m$ of the pin 9 (A_m being the active area of membrane) of F_S pushing force.
The connection 13, is welded to flange 11 and stiffened against this by a nut, respectively being rigidly and tightly mounted to the housing 6 and connected to the high pressure inlet (+) of the differential pressure sensor 14. So, by connection 13 is transmitted to the sensor 14 the sum of the pressure p_s of pushing force F_S and the static pressure p_f of fluid, provided by the transmission liquid, with which is previously fully filled the volume between the separation membrane and the sensing element of the sensor 14.
At the low pressure inlet (-) of the sensor 14, is coupled the static pressure p_f of fluid, taken by the connection 15, which is rigidly and sealed mounted on the housing.
Sensor 14 ensures a fully rigorous measurement of the differential pressure $\Delta p = (p_f + p_s) - p_f = p_s$, respectively the reaction pressure being structurally provided with the compensation function with the temperature and the pressure of the measuring fluid.
Thus the sensor 14 indirectly measures the pushing force F_S, implicitly the reaction force F_R and consequently measures the mass flow rate Q_m. The output signal of the sensor 14 is applied to the electronic block 16, where are stored both the calibration curve $Q_m = Q_m(\Delta p)$ according to the normal operating parameters of the measured fluid and the facility to be ensured the flow rate compensation with pressure and temperature of fluid. Thus the electronic block 16 renders the compensated value of the measured mass flow Q_m with P and T.
Since the pressure transmitting liquid between the separation membrane 10 and the differential pressure sensor is practically incompressible, the displacement of this membrane, implicitly of the pin 9, is therefore very small, almost null, to measure the entire range $Q_{m_{min}} \ldots Q_{m_{max}}$. Correspondingly, the reaction tube displacement is extremely small and consequently, this type of flowmeter is practically a flowmeter without moving

5. Reaction flowmeters with moving parts

These flowmeters are grouped, depending on the type of their reaction element, as follows:
- Reaction flowmeters with rotating reaction tube
- Reaction flowmeters with rotating reaction drum

Due to limited length of this paper, these flowmeters will be presented in another paper, and we now continue with the presentation of the experimental results regarding the reaction flowmeters without moving parts.

6. Experimental results and analysis

6.1 Reaction flowmeters with torque measurement
Further there are presented, the results of the experimental calibration successively achieved with water and air, for the reaction flowmeters with torque measurement.
Also the values of each experimental calibrations are presented in comparison with the values of the corresponding theoretical calibration.

6.1.1 Calibration with water
A reaction flowmeter of DN25 having a torque sensor (with τ_{max} = 0,5 Nm and accuracy 0,1%FS) has been calibrated with water (t = 20 ± 0,2^{0}C) by the gravimetric method. Table 1 presents the values both of the measured and of the calculated mass flow rate Q_m corresponding to the measured torque τ by the torque sensor of the calibrated flowmeter.
Corresponding to the measured torque range (0,0102…..0,5Nm) of its torque sensor, the potential measured flow rate range (310,152….2171,501 Kg/h) of

the calibrated reaction flowmeters was determined, experimentally and by theoretical calculation.

Table 1: Comparison between experimental and theoretical calibration with water

Torque	Pressure drop Δp	Average measured flow rate $Q_{m_{meas}}$	Theoretically calculated flow rate $Q_{m_{calc}}$	$\frac{Q_{m_{calc}} - Q_{m_{meas}}}{Q_{m_{meas}}} \times 100$
Nm	bar	kg/h	kg/h	%
0,01020	0,015	311,531	310,153	-0,44
0,02015	0,017	435,970	435,926	-0.01
0,02500	0,018	486,290	485,560	-0,15
0,03000	0,020	532,248	531,907	-0,07
0,04800	0,028	678,521	672,215	-0,93
0,07300	0,039	835,707	829,724	-0,71
0,10700	0,055	1014,740	1004,539	-0,98
0,15000	0,071	1199,002	1189,380	-0,80
0,20400	0,089	1400,101	1387,044	-0,93
0,25000	0,104	1549,122	1535,483	-0,88
0,32400	0,124	1761,315	1748,625	-0,72
0,35000	0,130	1830,906	1816,808	-0,77
0,40000	0,145	1957,716	1942,250	-0,79
0,45000	0,153	2076,891	2060,068	-0,81
0,50000	0,165	2189,455	2171,501	-0,82

The accuracy of the reaction flowmeter depends on the accuracy of the used torque sensor.
So, since the calibrated flowmeter used o torque sensor with τ_{max} = 0,5Nm and accuracy of, 0,1% FS, it has an accuracy of -(0,1% to 2% o.r.) corresponding to a theoretical turndown of 4,47, according to relationship $Q_{m_{max}}/Q_{m_{min}} = (\tau_{max}/\tau_{min})^{1/2}(0{,}5\text{Nm}/0{,}025\text{Nm})^{1/2}$
This value is confirmed and exceeded by the experimental turndown of 4,50, the ratio 2189,455Kg/h / 486,290Kg/h between the values of measured flow rate Q_m at torques 0,500Nm, respectively 0,025Nm.
The analysis of the Table 1 demonstrates a very good matching of the experimental and theoretical calibration, the percentage differences between the values of calculated and measured mass flow rate Q_m, being placed in a very narrow band of values of - (0,01….0,98)%.
The theoretical calculation of Q_m has been achieved using the customized form of general functional equation (7), according to construction of the calibrated reaction flowmeter, respectively:

$$Q_m = 97{,}2 \times (\rho \times \tau)^{1/2} \quad (11)$$

where:
Q_m - mass flow rate, in kg/h
ρ = 998,2 kg/m^3 - density of water for t = 20^{0}C
τ - measured torque, in Nm
97,2 - customized constructive constant, in m × s
Another positive conclusion it results from positioning of water velocities across the flowmeter with their maximum value (v_{max} = 1,22 m/s) in the center of the recommended economical velocity range.

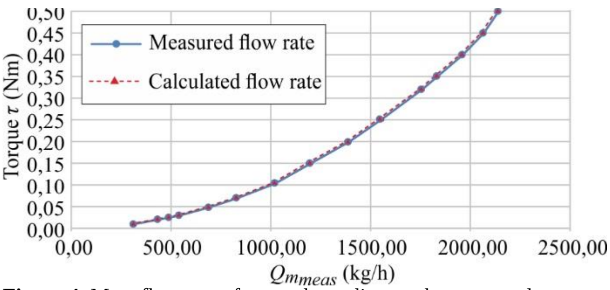

Figure 4: Mass flow rate of water depending on the measured torque

In Figure 4 there are plotted the dependence curves of Q_m by τ, both for theoretically calculated $Q_{m_{calc}}$ (red curve) and for measured $Q_{m_{meas}}$ (blue curve) flow rates, the density of water being practically constant during the calibration, at 20 ± 0,20 ^{0}C. It result a very good matching between these two convergent approaches, that ensures a strong basis for a predictable and coherent synthesis and design of any new type of reaction flowmeter.

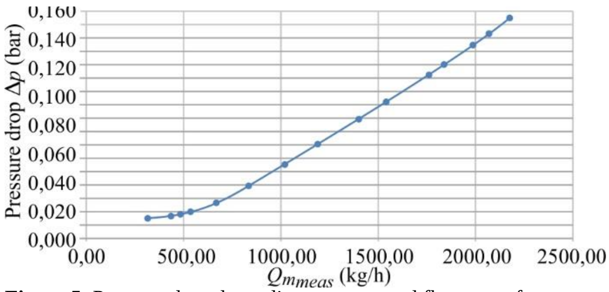

Figure 5: Pressure drop depending on measured flow rate of water

In Figure 5 is presented the curve of pressure drop Δp depending on flow rate Q_m .
It is observed that pressure drop Δp has a moderate value.
Regarding the installation these reaction flowmeters needs Inlet/Outlets of 0 × DN, being very economically.

6.1.2 Calibration with air
Another reaction flowmeter DN25 was calibrated with air. It has a dual-range torque sensor with measurement error 0,1% FS (that is custom-built to measure two ranges synchronously without chance-over) with the 1st range 0,5Nm and the 2nd range 1/10 of the 1st range, respectively 0 - 0,05Nm.

Table 2: Comparison between experimental and theoretical calibration with air

Torque	Inlet parameters of air				Pressure drop Δp	Average measured flow rate $Q_{m_{meas}}$	Calculated flow rate $Q_{m_{calc}}$	$\frac{Q_{m_{calc}} - Q_{m_{meas}}}{Q_{m_{meas}}} \times 100$
	Pressure P_1	Temperature t_1	Humidity	Density ρ				
O	bara	°C	%rH	kg/m3	bara	kg/h	kg/h	%
0,0025	0,9421	24,00	42,5	1,1030	0,0011	5,1120	5,1042	-0,15
0,0050	0,9432	23,67	42,7	1,1065	0,0020	7,2320	7,2298	-0,03
0,0100	0,9455	23,68	43,1	1,1110	0,0045	10,3740	10,2453	-1,24
0,0250	0,9520	24,12	42,6	1,1150	0,0110	16,5270	16,2284	-1,81
0,0500	0,9638	24,78	40,5	1,1270	0,0228	23,5340	23,0735	-1,96
0,1000	0,9855	26,51	35,5	1,1460	0,0445	33,5450	32,9048	-1,91
0,1500	1,0059	29,20	28,8	1,1580	0,0649	41,2950	40,5104	-1,90
0,2000	1,0286	32,81	24,4	1,1720	0,0876	47,9550	47,0593	-1,87
0,2500	1,0510	44,98	12,1	1,1500	0,1070	53,0620	52,1178	-1,78
0,3000	1,0690	44,99	12,2	1,1680	0,1280	58,4160	57,5372	-1,50
0,3500	1,0912	43,20	14,8	1,2010	0,1460	63,4000	63,0192	-0,60
0,3700	1,1008	34,10	20,7	1,2380	0,1575	66,0020	65,7852	-0,33
0,4200	1,1210	38,90	19,2	1,2500	0,1750	71,0020	70,4282	-0,81
0,4500	1,1277	40,02	18,5	1,3070	0,1910	74,7310	74,5437	-0,25
0,5000	1,1515	40,60	17,5	1,3320	0,2105	79,4190	79,3239	-0,12

The master slave method was used for the calibration.
In Table 2 is presented the comparison between the average values of the measured mass flow rate (according to experimental calibration) and the theoretically calculated flow rate, according to equation (7), corresponding to each measured torque τ, by the sensor of the calibrated flowmeter.
Also, in Table 2 for a complete analysis, the inlet parameters of air and the pressure drop are presented, for each value of the measured torque.
The torque sensor of the flowmeter being a dual - range sensor, when the torque value decreases along the 1st range, from 0,5Nm to 0,05Nm, the measurement error progressively increases from 0,1% o.r. to 1% o.r.
Then when the torque decreases, along the 2nd range, from 0,05Nm to 0,0025Nm, the measurement error progressively increases from 0.1% o.r. to 2% o.r.
It results that the whole used range of the torque sensor is characterized by the ratio
τ_{max} / τ_{min} = 0,5 Nm/ 0,0025Nm = 200.
Depending on the accuracy of the used torque sensor, results the accuracy of the reaction flowmeter.
In consequence, the measured errors of the reaction flowmeter repeats the variation of the dual - torque sensor, from 0,1% o.r. for $Q_{m_{min}}$ to 2% for $Q_{m_{max}}$.
This variation of the measurement errors corresponds to a turndown of the reaction flowmeters of $Q_{m_{min}}/Q_{m_{max}}$ = $(\tau_{max} / \tau_{min})^{½}$ = $(200)^{½}$ = 14,14, according to their functional equation (7).
The analysis of Table 2 demonstrates a very good matching of the flow rate values, experimental measured $Q_{m_{meas}}$ and theoretically calculated $Q_{m_{calc}}$; their percentage differences being placed in a narrow band of the values - (0,12…. 1,96)%.
The theoretical calculation of $Q_{m_{calc}}$ has been made with the equation (11), the customized form of the functional equation (7), that was established for using the torque sensor, according to constructive dimensions, and the values of the air density ρ.

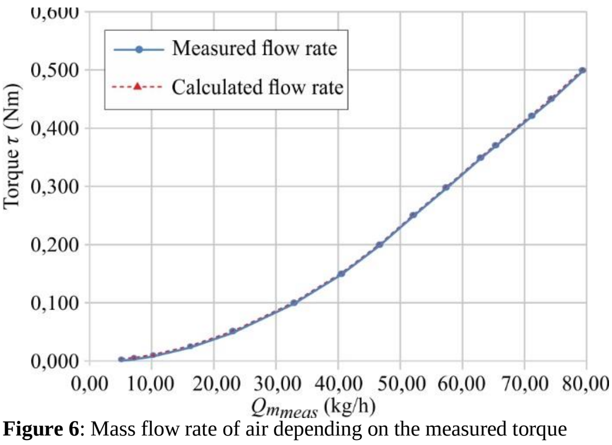

Figure 6: Mass flow rate of air depending on the measured torque

In Figure 6 is plotted the dependence curve Q_m by τ, both for the theoretically calculated $Q_{m_{calc}}$ (red curve), and for the measured $Q_{m_{meas}}$ (blue curve).
In result a very good matching between these two convergent approaches, that ensures a strong basis for a predictable and coherent synthesis and design of any new type of reaction flowmeter.

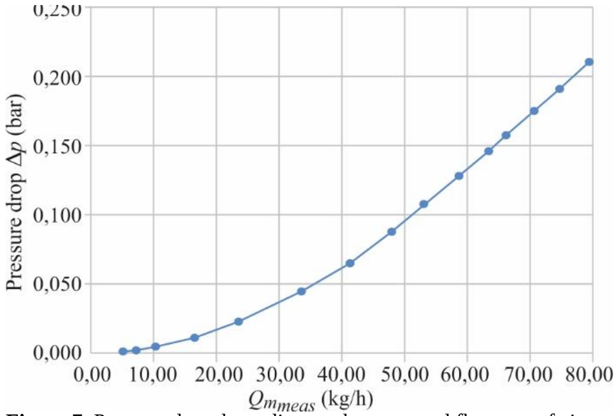

Figure 7: Pressure drop depending on the measured flow rate of air

In Figure 7 is presented the curve pressure drop Δp depending on the measured mass flow rate $Q_{m_{meas}}$. It is observed that Δp has a moderate value.
The comparison between the curves $Q_m = Q_m(\tau)$ achieved with water and air, for these two flowmeters DN25, demonstrates on the one hand, the correctness of the general functional equation (7) of the reaction flowmeters.
On the other hand it results the practical usefulness of the equation to be ensured for the calculation, with a good precision, of the flow rate value converted from a measured fluid to other measured fluid.

6.2 Reaction flowmeters with differential measurement of reaction pressure
This type of reaction flowmeters, with configuration presented in Figure 3, using a differential pressure sensor with a high accuracy of 0,02% FS, can ensure the measuring of mass flow rate Q_m with the accuracy of (0,1…2)% o.r., for a turndown of $(Q_{m_{max}}/Q_{m_{min}})^{1/2}$= $(\Delta p_{max}/\Delta p_{min})^{½}$ = $100^{1/2}$ =10.
The own microprocessor of the difference pressure sensor and respectively the electronic block of the whole reaction flowmeter ensure the complete compensation of measured Q_m with temperature (T) and pressure (P) of measured fluid.
These reaction flowmeters have advantage that can be used for a wide range of fluids (liquids and gases), including aggressive fluids, due to the fact that the material in contact with media of the differential pressure sensor is stainless steel ANSI 316 or viton.

7. Conclusion
This new flow measurement method offers, the theoretical basis of the design of a wide diversity of new types of flowmeters, for a large area of applications.
For the reaction flowmeters without moving parts there are established: the functional equations, the good fit between experimental and theoretical calibration, the main technical features (accuracy, turndown, pressure drop) and the possibilities of their future progressive improvements.

References
[1] Horia Mihai Moțit, *Unitary Analyssis, Syntesis, and Classification of Flow Meters* (Boca Raton, USA, CRC Press Taylor & Francis Group), 2018