Developments by a new flow measurement structure based on reaction force. Extended reaction flowmeters

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Abstract

There are presented the developments ensured by a new worldwide flow measurement structure, based on the reaction force, "the extended reaction flowmeter" ,elaborated by the first author, the subject matter of the patent application filed with European Patent Office EP 21020546, together other reaction flowmeters without moving parts.
Initially are synthetically reitered the constructive and structural specificities of "the extended reaction flowmeters "(shortly "ERF").
Then, starting from the facilities offered by the specific structural scheme of the ERF, significant simplified compared to that of the known compound flowmeters, are presented the developments offered by the using of this new flow measurement structure based on reaction force, by describing the improuved results achieved by two constructive variants of ERF, regarding the binomial of the two essential features (turndown and accuracy, interrelated of the flowmeters, by achieving a large extension of the turndown to very important values, correlated with an optimal range of the accuracy values.

1. Introduction

This new flow measurement structure, named "extended reaction flowmeter" (ERF), has been configured as a new result of the practical use of the "Computer – implemented Method" [2], Method developed as one application of the concept of "structural unity of all flowmeters", presented in book [1].
On the one hand, ERFs are characterized, different from the known compound flowmeters, by a new and simplified basic configuration, respectively a new mode of operation.
On the other hand, ERFs, due to the structural facilities offered by their simplified global configuration, combined with the specific configuration of their component flowmeters (reaction flowmeters without moving parts) provide very favorable condition for the elaboration of different constructive types which ensure a large extension of the turndown value, correlated with an optimal range of the accuracy values.
In this respect, the ERFs configuration has a simplified basic structure (comparing to that of the known compound flowmeters), by its achieving with a single "secondary element", used in common, but successively, by the two component flowmeters of ERF, by its successive coupling with each of the two "primary elements" of the respective flowmeters.
This successive coupling is achieved by a diverter that successively switches the flowing of the entered fluid, either through one or other from the two "primary elements", according to the operation algorithm of ERF, depending on the value of the instantaneous measured flow rate and of its variation tendency.
Thus is ensured the consecutive functional configuring of the two component flowmeters of ERF, each of them achieving the flow measurement along its specific flow rate range, according to the operating algorithm of ERF, being maximized the efficiency of this specificity
In this respect, there are initially presented the operating principle of ERFs (in connection with their basic configuration) and their functional equations.
Then, on these bases, are rendered and analyzed the experimental results obtained by two constructive types of ERF, regarding the values of the binomial (turndown and accuracy).

2. Operating principle and basic configuration of ERF

The operating principle of ERFs is presented together and related to their basic configuration, shown in Figure 1.
First of all, ERFs (according to previous mention) have a single "secondary element", different from the combined flowmeters, which are constituted by the parallel coupling of two flowmeters, both been complete configured (each having its own "primary element" and its own "secondary element").
In this respect, to the unique "secondary element" of ERF (composed concretely by force pick - up system 11, force sensor 12, and electronic block 5) are successively coupled, depending on the values of the measured flow rate, either the "primary element" of "the main flowmeter" (by its reaction tube 7), that measures the range of higher flow rates (thus, during this time sequence being achieved the assembly configuration of the "main flowmeter of the ERF", and its operation), or the "primary element" of "the secondary flowmeter", (by its reaction tube17), that measures the range of the lower flow rates (thus, during this time sequence being

achieved the assembly configuration of the "secondary flow meter of ERF", and its operation).
In this way, depending on the value of the instantaneous measured flow rate, according to the specific algorithm of ERF, “the secondary element“ of ERF is acted successively, either by "the primary element" of "the main flowmeter" with its reaction force F_{RM}, or by "the primary element " of "the secondary flowmeter", with its reaction force F_{RS}.
Secondly, the ERF specific operating algorithm, establishes a special functional correlation between the ranges of the two component flowmeters, which must be consecutive and complementary, having the values of one continuing with those of the other, with "a very small common overlap zone" between them, ΔQ_m.
Consequently, the entire ERF range is ensured by summing "the secondary range" $(Q_{min}^{S} \dots Q_{max}^{S})$, of the smaller flow rates, corresponding to "the secondary flowmeter", with "the main range" of the higher flow rates $(Q_{min}^{M} \dots Q_{max}^{M})$, corresponding to "the main flowmeter", minus their common overlap zone ΔQ_m, which has the expression:

$$\Delta Q_m = Q_{max}^{S} - Q_{min}^{M} \qquad (1)$$

ΔQ_m covers both the upper end of ”the secondary range” and the lower end of “the main range”, implicitly the entire flow range of the flowing switching from one component flowmeter to another and vice versa, being ensured the complete continuity of flow measurement during and along any functional switching.
We mention that $\Delta Q_m \leq 0{,}25\%$ of Q_{max}^{M}, being minimal in relation to the whole ERF range.

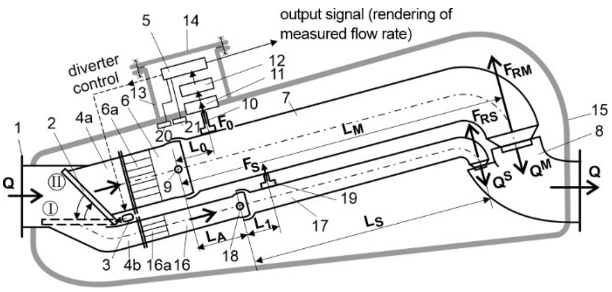

Figure 1: Basic structural scheme of the extended reaction flowmeters.

Legend:
1 – inlet connection of ERF (inlet connection of jet diverter), 2 – jet diverter, 3 – solenoid of diverter, 4a,4b – outlet connections of jet diverter, 5 – electronic block, 6 – immobile inlet tube of main flowmeter, 6a – flow conditioner, 7 – main reaction tube, 8 – common discharge connections of “extended reaction flowmeter”, 9 – shaft of main reaction tube, 10 – pin of main reaction tube, 11 – force pick-up system, 12 – force sensor, 13 – housing of ERF outer box, 14 – cover of ERF outer box, 15 – ERF housing (ERF body), 16 – immobile inlet tube of secondary flowmeter, 16a – flow conditioner, 17 – secondary reaction tube, 18 – shaft of secondary reaction tube, 19 – pin of secondary reaction tube, 20 – pressure sensor, 21 - temperature sensor.

As shown in Figure 1, the measured flow rate Q_m enters the ERF through inlet connection 1 (inlet connection of jet diverter 2).
Diverter 2, acted by its solenoid 3, switches the entered fluid to either outlet 4a, connected with the main flowmeter (for diverter in position I), or outlet 4b, connected with the secondary flowmeter (for diverter in position II), and vice versa, according to the command of electronic block 5
“The primary element” of „the main flowmeter”, consisting of the reaction tube 7, coupled with the immobile inlet tube 6 (potential provided with a flow conditioner 6a), and the fluid discharge connection 8, is specifically configured, and provided at its inlet with the shaft 9, perpendicular on it.
Thus is ensured a potential rotation mobility of tube 7 about the shaft axis, facilitating a rigorous measurement of the reaction force F_{RM} (generated by the flow rate Q^M), by the accurate measurement of the pushing force F_0, as its effect.
The reaction forces F_{RM} of "the main reaction tube" 7, respectively F_{RS} of "the secondary reaction tube"17 act at the distances L_M, respectively L_S from the axis of shaft 9, determining as their effect the pushing force F_0 (proportional to each of the two reaction forces, corresponding to the functional positions I or II of the diverter), exerted on the pin 10 placed on the main reaction tube 7, at a distance L_0 from the axis of shaft 9.
In turn, the pin 10, using the system 11, acts with this pushing force F_0 (proportional to reaction forces F_{RM} for diverter in position I, respectively F_{RS} for diverter in position II) the force sensor 12, whose electrical output signal is thus proportional to the pushing force F_0 (respectively to measured reaction force F_{RM} or F_{RS}), and implicitly to the measured flow rate Q_m.
The output signal of sensor 12 is applied to the electronic block 5, which has two simultaneous functions:
• calculation the values of instantaneous measured mass flow rate Q_m
• control of the diverter position, depending on Q_m values, according to ERF operating algorithm.
The blocks 5, 11, 12, are positioned inside the outer box of ERF (having housing 13 and cover14) that is rigidly fixed to ERF housing 15, and is not in contact with the measured fluid.
Force sensor 12 ensures the rigorous measurement of the force F_0, being rigidly fixed to the housing 13 in a properly positioning to the pushing force pick-up system 11
Similarly, the „primary element” of „secondary flowmeter” consists of the reaction tube 17, connected with the immobile inlet tube 16, potential provided with a flow conditioner 16a, and the flow discharge connection 8, which is common to both reaction tubes 7 and 17.
Reaction tube17 is provided with a vertical shaft 18, which ensures the potential rotation mobility of the tube about this shaft axis, and thus, facilitating a rigorous measuring of the reaction force F_{RS} (generated by the flow rate Q^S) by the accurate measuring of the output pushing force, as its effect.

The reaction force F_{RS} acts along the axis of the elbow of tube 17, at a distance L_S from the axis of shaft 18.
On reaction tube 17, at a distance L_1 from the shaft 18, is placed the pin 19, which pushes reaction tube 7 with force F_S. Under the F_S pressing, in turn, the reaction tube 7 presses the force sensor 12 with the force F_0, which is proportional to the force F_S, respectively F_{RS}, and implicitly with the measured flow rate Q^S.
Electronic block 5 calculates the instantaneous measured mass flow rate Q_m, compensated with pressure and temperature (due to sensors 20 and 21), the corresponding flow rate proportional signal being linearized and converted by the adapter electronics into an analog or usually digital signal.
Also the block 5, depending on Q_m values, commands the switching of the diverter position, according to the operation algorithm of ERF, presented in Table 1, which indicates the functional algorithm between the Measured Flow Rate and the Diverter Status.

Table 1: ERF operating Algorithm

Value of the Measured Flow Rate Q_m	Status (Position) of the Diverter	Main Line	Secondary Line
Q^S_{min} … Q^M_{min}	Position II	Closed	Open
Q^S_{max} … Q^M_{max} where: $Q^S_{max} > Q^M_{min}$	Position I	Open	Closed
$Q^S \uparrow = Q^M_{min}$ (Only, at the touching of value Q^M_{min}, for the increase tendency of the Q^S flow rate value)	Switching from Position II to Position I	Transition: closed to open	Transition: open to closed
$Q^M \downarrow = Q^S_{max}$ (Only, at the touching of value Q^S_{max}, for the decrease tendency of the Q^M flow rate value)	Switching from Position I to Position II	Transition: open to closed	Transition: closed to open

The complete continuity of the flow measurement along the entire ERF range is achieved by the functional ensuring of a very small overlap zone ΔQ_m of the ranges of the two component flowmeters of ERF (the main flowmeter and the secondary flowmeter), that practically covers completely the switching zone of the diverter 2.

3. Functional equations

3.1 Flow rate equations

The mass flow rate equation measured by the reaction flowmeters [3], has the general expression:

$$Q_m = (F_R \times \rho \times k^{-1})^{1/2} \qquad (2)$$

were:
F_R - reaction force exerted by the measured fluid on the reaction tube
ρ – fluid density
k - constructive constant
Consequently, according to ERF configuration, and to their operating algorithm (that commands, by the jet diverter 2, switching the passing of entered fluid, either through the main flowmeter, or the secondary flowmeter), results the two specific equations of the measured mass flow rate, as follows:

• Diverter in Position I:

$$Q^{\mathrm{I}}_{ERF} = Q^M = (F^{\mathrm{I}}_0 \times L_0 \times \rho \times k_M^{-1} \times L_M^{-1})^{1/2} \qquad (3)$$

where:
Q^{I}_{ERF} – ERF flow rate measured only by "the main flowmeter", respectively along the range (Q^S_{max} … Q^M_{max})
k_M – constructive constant of "the main flowmeter"
$F^{\mathrm{I}}_0 = F_{RM} \times L_M \times L_0^{-1}$ - output pushing force of ERF, for position I of diverter
F_{RM} – reaction force exerted by "the reaction tube" of "the main flowmeter"
L_0 – moment arm, with reference to the output pushing force F^{I}_0
L_M – moment arm, with reference to the reaction force F_{RM} of "the main flowmeter".

• Diverter in Position II:

$$Q^{\mathrm{II}}_{ERF} = [L_1 \times L_0 \times L_S^{-1} \times (L_1 + L_A)^{-1} \times \times F^{\mathrm{II}}_0 \times \rho \times K_S^{-1}]^{1/2} \qquad (4)$$

where:
Q^{II}_{ERF} – ERF flow rate measured only by "the secondary flowmeter", respectively along the range (Q^S_{min} … Q^M_{min})
K_S – constructive constant of "the secondary flow meter"
L_S – moment arm with reference to reaction force F_{RS} of "the secondary flowmeter"
L_1 – moment arm with reference to the output pushing force F_S
L_A – distance between the axes of shafts 9 (of the main reaction tube) and 18 (of the secondary reaction tube)
$F^{\mathrm{II}}_0 = (L_1 + L_A) \times F_S / L_S$ – output pushing force of ERF, for position II of diverter, is determined by the pushing of "the main reaction tube", by the pin 19 of "the secondary reaction tube" with force F_S, which is determined, in turn, by the reaction force F_{RS}
$F_S = F_{RS} \times L_1 \times L_S^{-1}$ - output pushing force of "the secondary flowmeter"
F_{RS} – reaction force generated by "the secondary reaction tube".
The measuring of the output pushing force F_0, using the same sensor 12 for both positions I and II of the diverter, requires mandatory to ensure the same maximum value of force F_0, corresponding to both the maximum value Q^M_{max}, of the flow rate measured by the main flowmeter (for position I of diverter) and the maximum value Q^S_{max}, of the flow rate measured by the secondary flowmeter (for position II of the diverter), resulting $F^{\mathrm{I}}_{0\,max} = F^{\mathrm{II}}_{0\,max}$.
In this respect, by processing is obtained the relationship between the maximum measurable flow rates by ERF, corresponding to its two functional configurations (as "main flowmeter", respectively as "secondary flowmeter"):

$$Q_{Mmax}/Q_{Smax} = [(1 + L_A/L_1) \times L_S \times \times k_S \times L_M^{-1} \times k_M^{-1}]^{1/2} \qquad (5)$$

3.2 Turndown equation

Turndown of any reaction flowmeter, can be rendered [3] also as the analytical relationship between the maximum permissible value of its accuracy E_{Fmax} *(% o.r.)*,

expressed as a percentage of reading of flow rate, and the accuracy E_{sensor} *(% o.f.s.),* of the sensor of its output pushing force (or its corresponding parameter, e.g. displacement), expressed as a percentage of the full scale rate.
Consequently, the turndown (T_M) of the main flowmeter, and the turndown (T_S) of the secondary flowmeter, have the equations:

$$T_M = Q_{Mmax} / Q_{Mmin} = = [E_{MFmax}\,(\%\,o.r.)/E_{Sensor}\,(\%\,o.f.s.)]^{1/2} \qquad (6)$$

$$T_S = Q_{Smax} / Q_{Smin} = = [E_{SFmax}\,(\%\,o.r.)/E_{Sensor}\,(\%\,o.f.s.)]^{1/2} \qquad (7)$$

Because both components of the ERF ("the main flowmeter" and "the secondary flowmeter") have the same value of the turndown ($T_M = T_S$), and use successively the same pushing force (or its corresponding parameter e. g. displacement) sensor, it results that the two components ensure the same maximum value of the flow measuring accuracy (expressed as percentage of reading of the rate), respectively that E_{MFmax} *(% o.r.)* = E_{SFmax} *(% o.r.)* = $E_{ERF\,max}$ *(% o.r.)*, it result a that the ERF turndown has the following equation:

$$T_{ERF} = \frac{\dfrac{E_{ERF_{max}}(\%\,o.r.)}{E_{\,Sensor}(\%\,o.f.s.)}}{1 + \dfrac{\Delta Q_m}{Q_{M_{max}}} \times \left[\dfrac{E_{ERF_{max}}(\%\,o.r.)}{E_{Sensor}(\%\,o.f.s.)}\right]^{1/2}} \qquad (8)$$

4. ERF with the measurement of the output force, proportional to F_R

4.1 Taking over and measuring the ERF output force
This constructive type of ERF respects the general basic configuration of ERF, presented in Figure 1, having its specific constructive configuration of the system 11, that ensures the taking over the pushing force F_0 (proportional to reaction force F_R) and its applying to sensor 12 (a force sensor with strain gauge).
The force sensor has the accuracy of 0.01% o.f.s. Because this force sensor with strain gauge is compatible with an industrial use, implicitly and this type of ERF also has the availability of an industrial use.

4.2 Experimental results and analysis
Further are presented the experimental results of the calibration with air of this specific configuration of ERF, achieved by the measurement of its pushing output force F_0, using this force sensor.
In this respect, in Table 2 is presented the variation of the reaction force F_R exerted by the fluid, depending on the measured mass flow rate Q_m, along the entire ERF range ($Q^S_{min} \cdots Q^M_{max}$), which is traveled (measured) by the correlated successive operating of “the secondary flowmeter" respectively of “the primary flowmeter", and vice versa, commanded by the electronic block 5, according to ERF operating algorithm.at the increasing and then at the decreasing of the flow rate.

Table 2: Reaction force depending on the measured mass flow rate of air

Q_m	F_R
kg/s	N
0,00017289	0,00001488
0,00033200	0,00005825
0,00079310	0,00034500
0,00101000	0,00054220
0,00145100	0,00116157
0,00175300	0,00164830
0,00237400	0,00310000
0,00244500	0,00365340
0,00786290	0,03858380
0,01592100	0,15760100
0,02327800	0,33527630
0,03097700	0,58137110
0,03357170	0,67672030

In connection with Table 2, in Figure 2 is plotted the curve of reaction force F_R depending on the measured mass flow rate Q_m of air, for this type of ERF with force sensor of its output force.
At the fluid flowing switching from the "secondary flowmeter" to the "main flowmeter", and vice versa, the value of the flow rate is very little modified, for a short time duration, being ensured the continuity of the flow measurement.
This is achieved due to both the narrowness of the switching zone ΔQ_m (of the overlapping the ranges of the two component flowmeters of ERF), the effect of the two flow conditioners, and of the software that ensures an efficient interpolation.

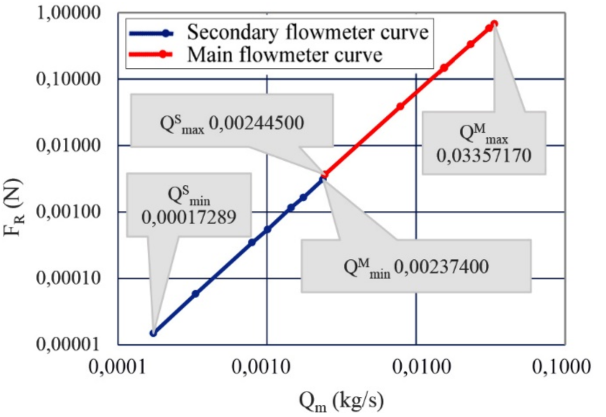

Figure 2: Reaction force curve depending on the measured flow rate of air

The theoretical considerations presented previously, regarding the binomial (the flow measurement accuracy - turndown), and implicitly the analytical their correlation, are confirmed by the results of the experimental calibration of ERF.
In this respect, the experimental turndown T^e_{ERF} = 0,0335717/0,00017289 = 194,18, confirms its theoretical value of T^t_{ERF} = 194,182 computed according to Equation (8), customized for $E_{ERF\,max}$ = 2% o.r., E_{Sensor} = 0,01% o.f.s ΔQ_m = 7,1 x10^{-5} kg/s, Q^M_{max} = 3,3517 x 10^{-2} kg/s.
In connection with the Table 2, in Figure 3 is shown, for this type of ERF, the accuracy curve, respectively the variation of E_{ERF} (% o.r.) depending on Q_m (kg/s).

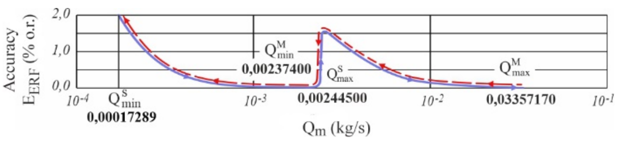

Figure 3: Accuracy curve

Table 3 presents the pressure drop Δp, depending on the measured mass flow rate Q_m,
In connection with Table 3, in Figure 4 is shown the curve of this dependence.

Table 3: Pressure drop depending on measured flow rate of air

Q_m	Δp
kg/s	bar
0,00017289	0,001
0,00033200	0,002
0,00079310	0,011
0,00101000	0,016
0,00145100	0,029
0,00175300	0,040
0,00237400	0,057
0,00244500	0,005
0,00786290	0,029
0,01592100	0,059
0,02327800	0,091
0,03097700	0,149
0,03357170	0,189

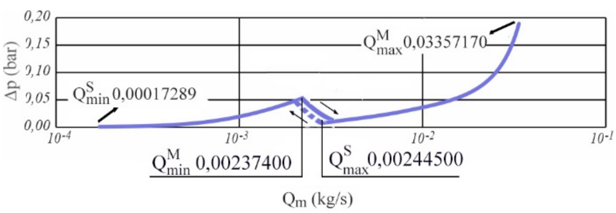

Figure 4: Pressure drop depending on measured flow rate of air

The diverter switching of the fluid flowing from the secondary reaction tube to the main reaction tube, or vice versa, depending on the tendency of increase or decrease of the flow along this overlap zone. ΔQ_m of ranges the two component flowmeters of ERF, determines a pressure drop, that occurs when the flow rate value is about 7% of the maximum flow Q^M_{max}, (in a very narrow overlap zone ΔQ_m which is about 0.22% of the Q^M_{max}).

5. ERF with measurement the balancing displacement of the reaction force

5.1 Taking over and the measurement the balancing displacement of the reaction force

This constructive type of ERF respects the general basic configuration of ERF, presented in Figure 1, having its specific constructive configuration for the system 11, which is coupled with the sensor 12.
Thus, this constructive solution has, coupled at its F_0 takeover block (achieved similarly with that of the constructive type of ERF, previously presented), a customized elastic element.

This element is acted by the pushing force F_0, which determines its elastic and linear small deformation. This deformation (displacement) is amplified, being obtained, for this value, a corresponding displacement with the maximum value of 12 mm.
This amplified displacement is permanently measured by a precise displacement sensor, having the measuring range of 12 mm, and the accuracy of ± 0.1µm (which, expressed as percentage accuracy, has the value of
$(0.1\times10^{-6}\text{m}) \times10^{-2} / (12 \times 10^{-3}\text{m} = 0.0008333$ % o.f.s.).
This constructive type of ERF is intended for laboratory conditions.

5.2 Experimental results and analysis

Further are presented the results of the experimental calibration with air of this specific configuration of ERF.
Table 4 presents the variation of the reaction force F_R exerted by the fluid, depending on the measured mass flow rate Q_m, along the entire ERF range $(Q^S_{min} \dots Q^M_{max})$, traveled by the successive operating of the "secondary flowmeter" respectively the "main flowmeter", and vice versa, commanded by the block 5, according to ERF operating algorithm, at the increasing and then at the decreasing of the flow rate.

Table 4: Reaction force depending on the measured mass flow rate of air

Q_m	F_R
kg/s	N
0,0694440	2,81610000
0,0482010	1,35680000
0,0282010	0,46450000
0,0102110	0,06089000
0,0075100	0,03294000
0,0050110	0,01465000
0,0014600	0,00124400
0,0014175	0,00117300
0,0008502	0,00052700
0,0008120	0,00038500
0,0006010	0,00021100
0,0002120	0,00002620
0,0000910	0,00000480
0,0000602	0,00000210
0,0000298	0,00000053

In connection with Table 4, in Figure 5 is plotted the curve of the reaction force F_R depending on the measured mass flow rate Q_m of air, for this type of ERF.

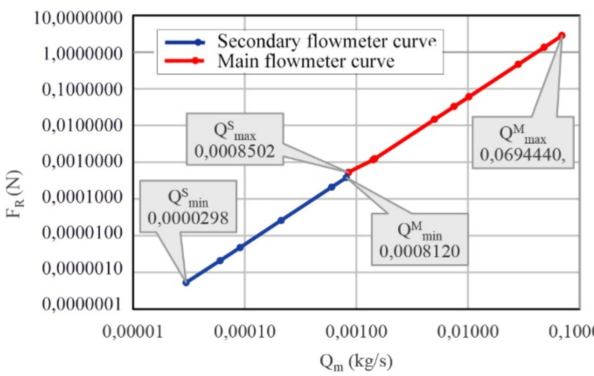

Figure 5: Reaction force depending on the measured mass flow rate of air

The theoretical considerations presented above, regarding the binomial (the flow measurement accuracy - turndown), and implicitly the analytical correlation between them, are confirmed by the results of the experimental calibration of ERF.

In this respect, the experimental turndown T_{ERF}^{e} = 0,069444/0,0000298 = 2330,336 confirms its theoretical value of T_{ERF}^{t} = 2330,138 computed according to Equation (8), customized for $E_{ERF\ max}$ = 2% o.r., E_{Sensor} = 0,0008333 % o.f.s.,Q_{max}^{M} = 6,9444 × 10^{-2} kg/s and ΔQ_m = 4,25 ×10^{-5} kg/s

In connection with the Table4, in Figure 6 is shown, for this type of ERF, its accuracy curve, respectively the variation of E_{ERF} (% o.r.) depending on Q_m (kg/s).

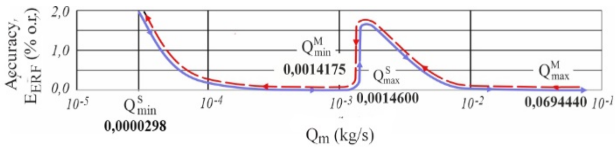

Figure 6: Accuracy curve of ERF

The curve allure, of the pressure drop Δp depending on the measured flow rate Q_m, is similar with that shown in Figure 3, for the previous presented type of ERF.

6. Conclusions

This new flow measurement structure, the "extended reaction flowmeter", on the one hand has a significant simplified basic configuration, compared with that of the known compound flowmeters.

On the other hand, as has been presented above by the two developed constructive types, ERF offers the theoretical and structural bases for the design of a diversity of new constructive types with significant increased values of the turndown, corresponding to a optimum range of the accuracy values, respectively the possibility of their future concrete development.

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