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THE EFFECT OF DOUBLE VENTURI'S STRUCTURAL PARAMETERS ON THE REINFORCEMENT VALUE AND FLOW COEFFICIENT

Reinforcement factor of a double Venturi is one of the more important parameters related to sensor shape and structure. The evaluation and the effect of the double Venturi's structural parameters on its value were carried out by means of the regression equation obtained from numerical simulation tests conducted by means of the Fluent program and planned experimental techniques. The presented test results indicate that the largest effect on reinforcement, within the tested field, was the throat diameter of the internal Venturi and the diffuser length of the external Venturi.

The second important parameter of a double Venturi is the flow coefficient K. The analysis of construction parameters was also carried out by means of the regression equation. The parameters which, when enlarged, cause the reduction in the flow coefficient (K) range are: the diffuser length of the external Venturi, and the first-degree interaction between the internal diffuser length and the internal Venturi's throat diameter. Simulation test results and conclusions have been supported by experimental results.

Keywords: double Venturi tube, flow-rate measurement, metorological analysis

1. INTRODUCTION

Fluid flow measurements, conducted by means of various methods, belong to the most frequently encountered types of measurement in laboratory and industrial practice. Such measurements occupy an important place within the larger field of engineering problems related to the operation of both individual machinery and whole systems. The measurements are applied, among others, to the management of technological processes, the distribution of energy carriers, or frequently constitute the basis for mutual adjustment.

The diversity of methods in measuring mass flow and volume result from the use of different physical phenomena which accompany the flow and combine with a large assortment of measuring apparatus offered by manufacturers of control and measuring devices.

The physical complexity of flow problems makes it difficult to approach these processes from a mathematical standpoint. Hence, a large role is played by experimental research and mathematical modeling of flows.

The selection of an appropriate type of flowmeter requires a thorough knowledge of data related to both the nature of flow, especially its dynamics, fluid type and its physical parameters, and to the scope of its changeability and variability interval of fluid flow. Other essential elements are the requirements of measurement accuracy and the data related to the installation in which the flowmeter is supposed to be installed.

Answers to the questions raised above constitute the basis for proper design of the fluid flow measuring system.

Computer simulation is the tool which significantly limits the costs and the duration of experimental research connected with flowmeter testing. Calculation results obtained by way of such simulations create a significant problem in terms of their credibility. This is also related to the choice of a calculation method selected from a wide range of simulation programs available on the market. A significant discrepancy in results might be obtained even when the whole group of programs employs identical CFD algorithms (Computational Fluid Dynamics).

Numerical flow dynamics, despite the fact that it is still a developing field, is a serious cognitive apparatus of complex flow processes, including the ones in Venturi. It should be emphasized that the aim of computer simulations is to supplement the experiment. Conducted analysis of numerical visualizations helps to gather answers to a whole series of questions concerned with the formation of vortexes within the double Venturi, the kind of answers to questions one could not obtain by way of experimental research, and that only attests to the huge potential of modern CFD techniques.

According to the authors, from the available two-equation models of turbulence [1, 2], only the Wilcox k-ω model [3, 4] allows to localize the boundary layer separation point with greater precision.

Numerical test results presented by the above-mentioned authors have been supported by their own experimental research discussed in this paper [5, 6].

2. THE EFFECT OF DOUBLE VENTURI'S STRUCTURAL FEATURES ON THE AMPLIFICATION VALUE

The analysis of individual parameters characteristic of a double Venturi geometry was carried out by means of *the regression equation*

$$y = A_0 + A_! x_1 + Aix_i + \mathbf{B}12x_1x_2 + B_{in}x_ix_n + \delta \tag{1}$$

in which δ stands for the rest (remainder). The assumed regression model formulated a linear dependence of examined parameters (coefficients A), supplemented by a non-linear part with interacting parameters (coefficients **B**) at the appropriate levels of two-level plans. Interactions of the 1st, 2nd and 3rd degree were taken into consideration. To simplify the procedure, standardization of input variables was applied.

Simulation tests were conducted by means of the planned experimental techniques [7] using research plans based on the type 2^5 two-level plan. These plans meet the conditions of experimental symmetry, orthogonality, and sum square equalities in all the columns of the experimental matrix.

On the basis of personal experience, acquired from earlier simulations and experimental tests of a single Venturi, the following assumptions have been made with regard to the double Venturi structure:

The outlet section of the internal Venturi diffuser lies in the frontal plane of the external Venturi throat; angles of flare for the internal and external Venturi diffusers are the same and measure 14°; the angle of flare for the convergent pipe of the internal Venturi measures 22°; internal Venturi contains 0.1 module.

The following input variables have been assumed:

x_1 – double Venturi module $m_2 = F_g/F_{k2}$ (double Venturi module m_2 – ratio of cross-section surfaces, where pressure impulses are taken), in the range of $(0.01 \div 0.02)$,

x_2 – diffuser length of internal Venturi denoted as l_{d1} within the range of $(14 \div 54)$ mm,

x_3 – diffuser length of external Venturi denoted as l_{d2} within the range of $(120 \div 240)$ mm,

x_4 – throat diameter of internal Venturi denoted as d_{g1} within the range of $(6 \div 12)$ mm,

x_5 – the ratio of flux surfaces effect to external Venturi throats $S = F_{gD}/F_{Dm}$, within the range of $(1 \div 3)$.

Figure 1 shows the diagram of the Venturi with relevant denotations.

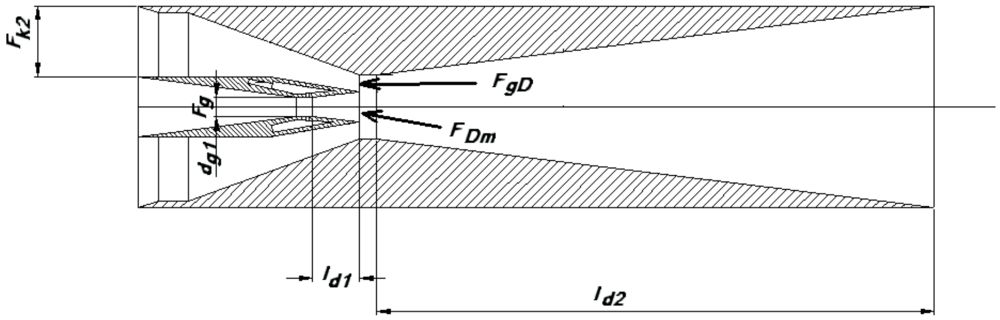

Fig. 1. Venturi diagram.

Venturi reinforcement was assumed as an output variable (the ratio between pressure concentration on the Venturi and the dynamic pressure of the inflowing flux):

$$Z = \frac{2\Delta p}{v^2 \rho}. \tag{2}$$

As a result of the calculations and the selected test results, the regression equation has been obtained

– when flux inflow velocity to Venturi is 5 m/s for standardized variables

$$\begin{aligned} Z_5 = 8.525 + 1.405 * d_{g1} + 0.9541 * l_{d1} + 0.8194 * l_{d1} * d_{g1} + \\ +0.748 * S - 0.7194 * m - 0.4194 * m * d_{g1}, \end{aligned} \tag{3}$$

- when flux inflow velocity is 20 m/s

$$\begin{aligned} Z_{20} = 12.6228 + 1.9897 * d_{g1} + 1.898 * l_{d2} + 1.0285 * S - 0.8114 * l_{d1} - \\ -0.6553 * m + 0.528 * l_{d1} * d_{g1} - 0.523 * m * S - 0.5089 * d_{g1} * S \end{aligned} \tag{4}$$

As a result of the conducted calculations, regression equation statistics have been obtained for which the square of the Pearson correlation coefficient measured 0.9168 while the Venturi inflow velocity was 5m/s (3) and 0.9544 when inflow velocity measured 20m/s (4). In both cases, the variance analysis showed the significance of using regression equation, even at a probability of 99%.

The analysis of regression Eq. (3) demonstrates that there are only six significant coefficients. The Venturi's throat diameter has the largest effect on reinforcement. The effect of diffuser length and the interaction of the internal Venturi's throat diameter and internal diffuser length can be evaluated as being at the same level. In light of the obtained results, one cannot confirm the significance of the effect the internal Venturi diffuser length has. Both the Venturi module coefficient and the coefficient of the module interaction and the internal Venturi throat are negative in value (an enlargement of these parameters causes a reduction in Venturi strength).

From the analysis of regression Eq. (4) one can conclude that the number of significant parameters has increased to eight. The largest effect on reinforcement has, as before, the throat diameter of the internal Venturi. Diffuser length of the external Venturi has almost the same effect. Together with an increase in length (diffuser length of external Venturi), the Venturi reinforcement increases. The third parameter which has a significant effect is the inflow surface ratio S. The above coefficients have a positive sign which means that Venturi reinforcement increases along with increasing parameters.

An increase in the diffuser length of the internal Venturi reduces the reinforcement. A module increase has the same effect as the coefficients of these parameters have a negative sign. As a result of these experiments, a mathematical model was created for double Venturi reinforcement that can be used for prediction (on the basis of these results, physical models of double Venturi were carried out and were subsequently tested at the experimental stand in order to verify the accuracy of the mathematical model and to give a preliminary description of the Venturi characteristics).

A mathematical model of Venturi reinforcement can be used to show the effect of selected parameters on the reinforcement value, Figs. 2 – 4.

Figure 2 shows the effect the internal Venturi's throat diameter and module have on the reinforcement value when the value of the remaining parameters are at the upper end of the assumed interval of the research plan.

An increase of the internal Venturi's throat diameter leads to an increase in Venturi's reinforcement. With the given throat diameter of the internal Venturi, the effect of the module is insignificant. The largest reinforcements were obtained for module 0.01 and for the largest tested Venturi throat diameter of 12mm.

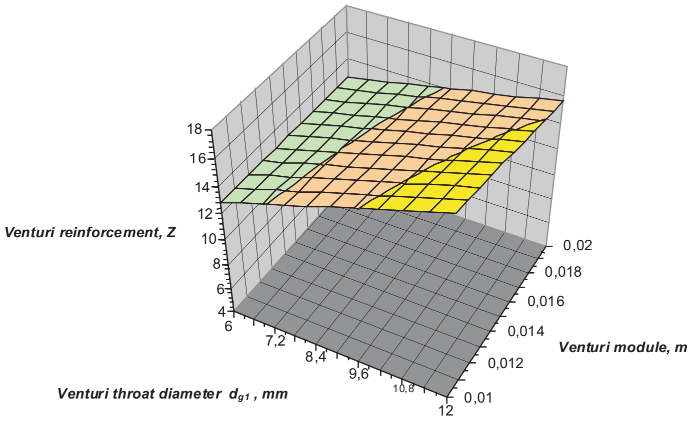

Fig. 2. The effect of the throat diameter and module on the reinforcement value with the upper values of the remaining parameters of the assumed research plan.

Figure 3 shows the compared effects between diffuser length and Venturi reinforcement. The diffuser length of the external Venturi has the largest effect on the reinforcement value. A decrease of the internal Venturi's diffuser length leads to an increase in reinforcement. The largest reinforcement was obtained for the smallest internal diffuser length and the largest (for the entire tested area) diffuser length of the external Venturi. In order to obtain the largest reinforcement, double Venturi's external diffuser should have the largest possible length while the internal diffuser the smallest length.

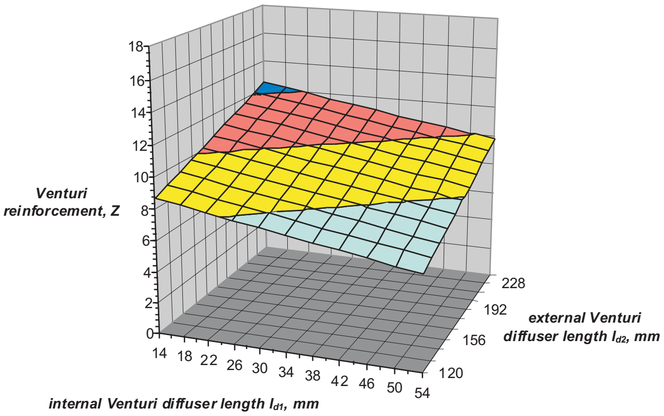

Fig. 3. The effect of internal and external Venturi length on the reinforcement value with the bottom values of the remaining parameters of the assumed research plan.

Figure 4 shows the effect of throat size and external Venturi's diffuser length on the reinforcement value.

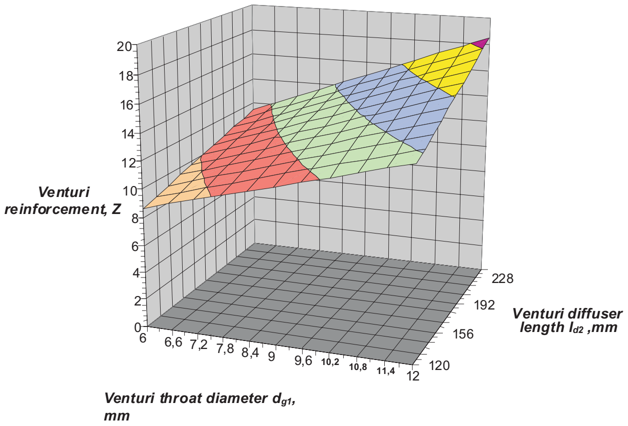

Fig. 4. The effect of diffuser length and throat diameter on Venturi reinforcement with the bottom values of the remaining parameters of the research plan.

One can see from the diagrams that double Venturi reinforcement decreases along with the decreasing diffuser length of the external Venturi. From the conditions presented in the diagrams, one can see that by increasing the throat diameter of internal Venturi one increases the reinforcement value. The largest reinforcement was obtained with the largest diffuser length and the largest throat diameter.

3. THE EFFECT OF VENTURI'S STRUCTURAL FEATURES ON THE STABILITY VALUE OF THE FLOW COEFFICIENT

The dependence between the local flow velocity and the measured pressure difference Δp, can be written in the following way:

$$v = K' \sqrt{\Delta p}. \tag{5}$$

Flow coefficient K' allows for the effect of sensor structure and shape (of Venturi) on the obtained concentration value. Interval range (the difference between the maximum and minimum value of coefficient K) was assumed as the measure of coefficient stability. This range ΔK was assumed as an output variable.

The effect of Venturi's structural features on the value of flow coefficient stability was carried out by means of the regression equation analysis. The value of coefficient K' was determined for the inflow velocity of 5 m/s and the velocity of 20 m/s. Tests were conducted on the basis of the same research plan and the same input variables as well as their values expressed in the simulation tests of a double Venturi.

As the result of calculations and the analysis of results, the following equation has been obtained:

$$\begin{aligned}\Delta K &= 0.0628 - 0.0096 * l_{d1} - 0.0077 * l_{d1} * d_{g1} + 0.0075 * l_{d1} * S + 0.0073 * m_2 - \\ &-0.0066 * l_{d2} * d_{g1} * S + 0.0060 * l_{d1} * l_{d2} * m_2 * d_{g1} * S\end{aligned} \tag{6}$$

Regression equation statistics demonstrate the adequacy of the description. The Pearson correlation coefficient measured 0.7224 while the variance analysis demonstrated the significance of the description by means of the regression equation, even at the probability of 99%.

From the presented regression Eq. (6) one can conclude that all the parameters have the same effect inspite of the fact that three coefficients have a negative sign. The parameters which, when enlarged, trigger a decrease in boundary ranges ΔK are:

diffuser length of external Venturi,

interactions of the 1st degree;

diffuser length of internal Venturi and the length of internal Venturi's throat diameter, interactions of the 2nd degree;

diffuser length of external Venturi and the length of internal Venturi's throat diameter and of the inflow surface ratio *S*.

The influence of certain parameters, characteristic of Venturi geometry, seems to be of contradictory nature. On the one hand, it is advantegous to increase Venturi reinforcement; on the other, by increasing reinforcement, one increases the nonlinearity of characteristics. A comparison was made between two Venturis, which differ only in terms of the internal Venturi's throat diameter – in the first instance 4, in the second 10mm. An increase in the throat diameter caused a reinforcement increase by about 15% (a reinforcement increase from 14.89 to 17.64 at the flow velocity of 20m/s). Simultaneously, the interval range ΔK has tripled, from 0.0195 to 0.0658.

Figures 5 to 8 show the effect of selected parameters on the value ΔK within the velocity range of 5- 20 m/s.

The dependence of flow coefficients' interval range on double Venturi module and surface ratio 5 is shown in Fig. 5. Flow coefficient is more stable for the upper values of the assumed parameters. The smallest values were obtained for a 0.01 module and the surface ratio is equal to 3. The increase in surface ratio S when module equals 0.02 causes the increase in ΔK, the reverse of the situation when module equals 0.01. From the diagrams one can see that the best results, in terms of flow coefficient range, are obtained for the largest surface ratio *S*.

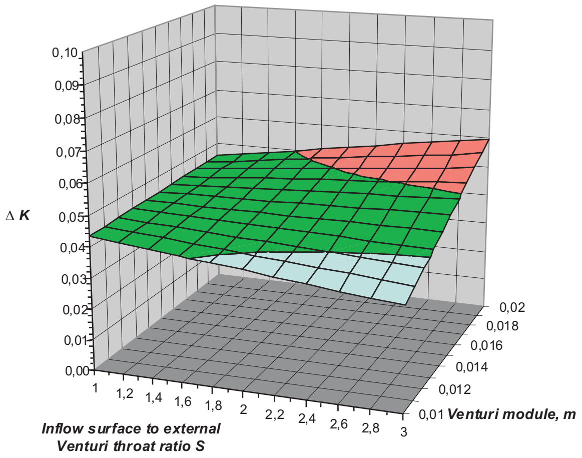

Fig. 5. The dependence of flow coefficient ΔK on module and surface ratio S with the upper values of the remaining parameters of the research plan.

Figure 6 shows the effect of module and internal Venturi's throat diameter on the flow coefficient's interval range. The smallest dispersion of flow coefficients ΔK occurs when the throat diameter is the largest and the module the smallest. A decrease in internal Venturi's throat diameter causes an increase in ΔK.

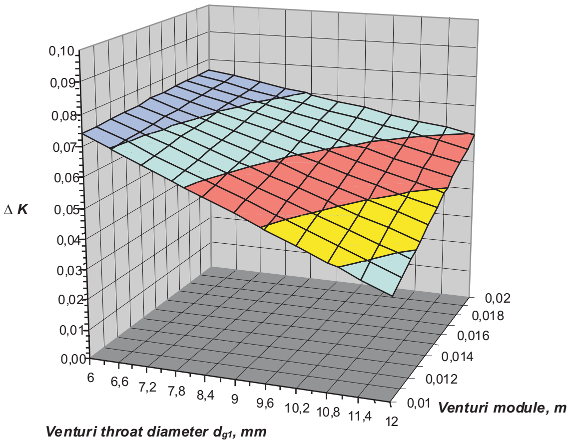

Fig. 6. The dependence of flow coefficient ΔK on the module and diameter of internal Venturi throat with the upper values of the remaining parameters of the research plan.

Figure 7 shows the dependence of interval range of flow coefficient ΔK on the module and on the internal Venturi's diffuser length.

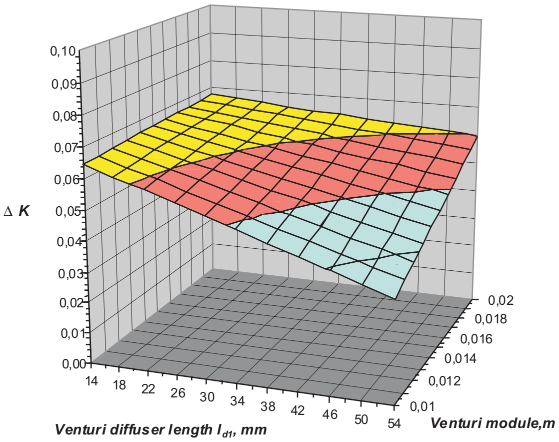

Fig. 7. The dependence of flow coefficient ΔK on the module and length of internal Venturi diffuser with the upper values of the remaining parameters of the research plan.

The increase in internal Venturi's diffuser length leads in every case, although to a various degree, to a decrease of ΔK, regardless of the assumed module $\boldsymbol{m_2}$.

The smallest range of the flow coefficient ΔK can be achieved with the smallest module, the largest internal Venturi diffuser, and when the values of the remaining parameters are at the upper range of the assumed research plan interval.

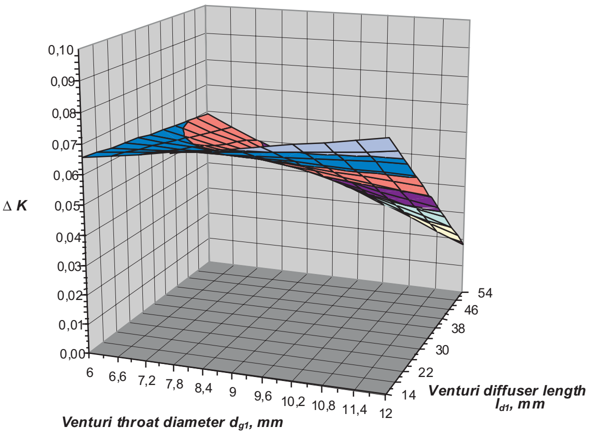

Fig. 8. The dependence of flow coefficient ΔK on throat diameter and length of internal Venturi diffuser with the bottom values of the remaining parameters of the research plan.

Figure 8 shows the dependence of the coefficient range on throat diameter and internal Venturi diffuser length. The smallest value of ΔK is accompanied by a large diffuser length, large throat diameter of internal Venturi, and the lower values of the remaining parameters assumed for the research plan interval. In those cases, an increase in throat diameter causes an increase in ΔK when the internal Venturi's diffuser length is small, and a decrease of diffuser length when the values are large.

When the values of remaining parameters are at the upper end of the assumed research plan internal, an increase in the throat diameter leads to a decrease of ΔK when the values of internal Venturi's diffuser length are both small and large.

4. VALIDATION OF SIMULATION TEST RESULTS

On the basis of the obtained regression equation for double Venturi, a real life Venturi model was made, as shown in Fig. 9.

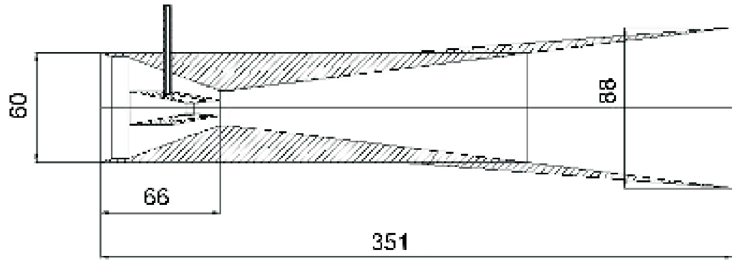

Fig. 9. Diagram of a double Venturi.

For this Venturi, we should obtain Venturi reinforcement of 14.91 for a flow velocity of 20m/s and 9.59 for a velocity of 5m/s, according to Eqs. (4) and (5).

Figure 10 shows the characteristics obtained from experiments. For the flow velocity of 5m/s, a reinforcement of 9.82 has been obtained and 13.4 for the flow velocity of 20m/s. A deviation of the expected reinforcement from the one which was experimentally obtained, results from the increase in flow resistance and disruption caused by the installation of the internal Venturi and by a redirection of the pressure impulse from internal Venturi throat, but not from regressions allowed for in the equation.

It should be noted that such deviations vary with different flow velocities and for velocities below 8m/s such an effect can be disregarded. Figure 10 shows simulation test results when turbulence model $k-\varepsilon$ and model $k-\omega$ are applied. One can clearly observe here an over-increase in reinforcement for model $k-\varepsilon$ and good convergence of experimental test results and simulation results for model $k-\omega$.

Figure 10 also shows the results of the obtained reinforcement according to simulation tests which have been carried out by means of the turbulence model $k-\varepsilon$ and model $k-\omega$. One can clearly observe here an over-increase in reinforcement for model $k-\varepsilon$ and good convergence of experimental test results and simulation results for model $k-\omega$.

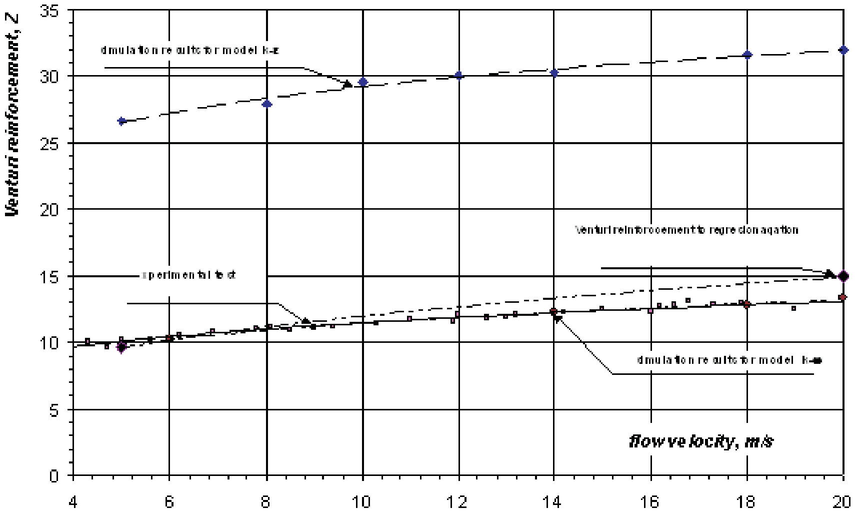

Fig. 10. Venturi reinforcement for different flow velocities.

5. CONCLUSION

The combination of two techniques, computer simulation of numerical calculations and planned experimental techniques, allows to achieve the following:

– increased accuracy of obtained results and significantly reduce measurement time,

– obtaining results and evaluating them, which is not an easy thing to do when the results are obtained by means of traditional measuring techniques,

– decreases Venturi size while Venturi similarities are maintained, triggers a reinforcement decrease (the effect of throat diameter on reinforcement value),

– the main cause of the decrease in Venturi reinforcement is the local resistance, which results from the appearing flow turbulence,

– the highest convergence of calculation results with experimental results was obtained for turbulence model $k - \omega$,

– model $k - \varepsilon$ assumed for the calculation gave twice as much pressure in comparison to model $k - \tilde{\omega}$. This is why one should be cautious when comparing Venturi reinforcement results, especially calculation results, and pay attention to conditions under which the results were obtained.

– when flow velocity is small, the Venturi throat diameter has the largest effect on Venturi reinforcement,

– when flow velocity is large, the largest effect on Venturi reinforcement have the internal Venturi throat diameter, external Venturi diffuser length and the inflow surface ratio S. Venturi reinforcement increases along with the increasing parameter values,

– when inflow velocity is large, the enlargement of the internal Venturi's diffuser length and module value create a decrease in reinforcement,

– in order to obtain the largest reinforcement, a double Venturi should be constructed with possibly the largest external diffuser length and the smallest internal diffuser length,

– reinforcement increases along with decreasing internal Venturi diffuser length. With a single Venturi, an increase in diffuser length causes an increase in reinforcement,

– the smallest flow coefficient ΔK occurs simultaneously with the largest throat diameter and the smallest module,

– the shortening of the extrenal Venturi leads to a reduction in reinforcement for all inflow velocities,

– linear regression equation enforced a relatively small variability range of geometric parameters that, in the case of Venturi throat, was between 6-12 mm in the experiments conducted up to this point,

– the research on double Venturi should encompass structural solutions with Venturi throat diameter larger than 12mm.

It is essential to conduct research based on the enlargement of the variability range of structural parameters. The limitations imposed so far on the size of internal Venturi's throat diameter involved the limitations placed on double Venturi size with module 0.01 for double Venturi and 0.1 for single Venturi.

A full research, based on the wide variability range of internal Venturi throat, could lay the grounds for studies on the optimization of Venturi size in order to maximize reinforcement or flow coefficient stability and corresponding reinforcement.

6. NOTATION

Δp – pressure difference in Venturi,
k – turbulence kinetic energy,
ε – kinetic dissipation velocity of turbulence energy,
ω – specific dissipation velocity of kinetic turbulence energy,
v – fluid velocity,
Z – Venturi reinforcement,
ρ – fluid density,
A – steady,
B – steady,
δ – the rest (remaining),
d_g – Venturi throat diameter,
F – surface,
l_d – diffuser length,
l_k – confusor length,
m – Venturi module,

K – flow coefficient,
S – inflow surface to external Venturi throat ratio,

Index 1 refers to internal Venturi,
Index 2 refers to external Venturi.

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