Analysis of velocity distribution in an air flow through a thin perforated plate

Adam Groma[1*], *Adam* Kazda[1], *Michal* Kotek[2], *Darina* Jašíková[2], and *Adam* Kuře[2]

[1]VÚTS, a.s., Department of Computation and Modelling, Svárovská 619, 460 01 Liberec, Czech Republic
[2]Technical University of Liberec, Faculty of Mechatronics, Informatics and Interdisciplinary Studies, Studentská 2, 461 17 Liberec, Czech Republic

Abstract. Modelling air flow in a curved fine perforated plate region was performed by porous zone substitution. This approach significantly simplifies the observed process, thus various limitations appeared. PIV measurements on an experimental test rig were performed and compared with the results from CFD computations.

1 Introduction

Perforated plates find their use throughout various industries. The most common perforated plate applications in fluid dynamics are with filtration, different particle size separation, flow homogenization or pressure drop control or throttling. Although a fluid flow through a perforated plate in a normal direction is often studied and well-described phenomenon, a flow hitting a plate under an acute angle is more complex and much less investigated.

An impact of a perforated plate on a fluid flow highly depends on both flow and plate properties. Particularly important are fluid viscosity, density and flow velocity magnitude and direction for the flow and orifices shape and plate thickness for the plate.

Porous Zone (PZ) model defines a source term in momentum equation composed of viscous loss taking into account viscosity and linear velocity dependence and inertial loss taking into account density and quadratic velocity dependence. Both terms include empirical coefficients defining specific properties of the porous zone itself. Thus, the model is widely used for perforated plate representation where the plate orifices properties are covered in the empirical coefficients.

To determine viscous and inertial loss coefficients of the perforated plate, various studies were executed on an experimental [1] and numerical [3-4] basis. Also, several analytical relations [4-5] and experimental methods were developed and described for this purpose. Nevertheless, the studies typically consider flow direction normal to the perforated plate.

In this study, an air flow through a curved perforated plate is investigated experimentally and numerically. First Particle Image Velocimetry (PIV) is used to visualize velocity distribution in the air flow. Further the results are compared with a numerical study using the porous zone model for the perforated plate with different means of porous zone properties evaluation. Suitability of the used porous zone properties evaluation represents a topic of further discussion and investigation.

2 Experimental setup

The experiment took place at the Technical University of Liberec where a test rig was designed and constructed. The rig scheme is shown in Fig. 1. The monitored geometry consists of an 80 x 80 mm square cross-section channel which is straight at the beginning to allow velocity profile development, before the end it is curved by 90° and it ends in a closed section. The outer (upper) wall of the curved part is made of a perforated plate and above it, a second channel is widening from the beginning of the curve to its end. The end of the second channel is connected to a suction device. Thus, all the air in the rig flows from the air inlet through the perforated plate to the suction device.

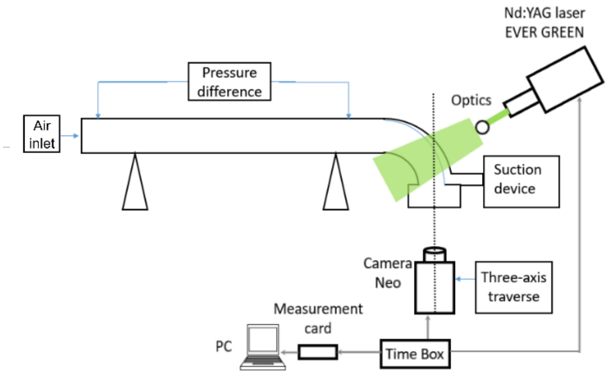

Fig. 1. Experimental setup for PIV measurements.

For the air flow behaviour and its velocity distribution also the perforated plate properties are important. The used plate has a constant thickness and is varnished. The perforation consists of constant radius circular holes pattern with specified axial spacing. The thickness of the plate including varnish is similar to hole diameter.

* Corresponding author: adam.groma@vuts.cz

3 PIV measurement results

Measurements were performed for three mean air flow velocities of 4 m/s, 5.7 m/s and 7 m/s. The mean air flow velocity was measured in the straight part of the channel.

The PIV method was used to evaluate the vector velocity distribution field in the curved channel area where the perforated plate is located. Velocity distributions for mean velocity 4 m/s, 5.7 m/s and 7 m/s are displayed in Fig. 2, Fig. 3 and Fig. 4 respectively. It is obvious that the distribution in the observed area has the same character in case of all three mean velocities. In the square channel, the velocity magnitude is steady along the curved region except for near the bottom wall. Here the flow velocity slightly decreases from the beginning of the curve and before the reach of the perforated plate end a significant drop occurs. Due to the immense air outtake at the end region, the flow velocity drops significantly in the whole cross-section. In the channel above the perforated plate, the velocity magnitude is steadily increasing along the curve and it reaches its maximum at the end of the curved part where the suction unit is connected.

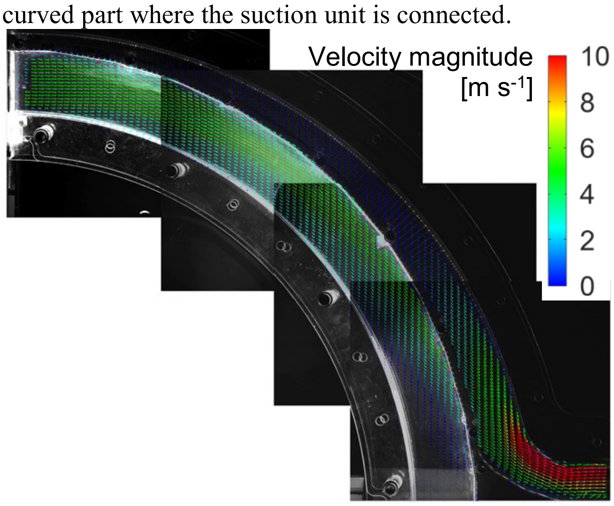

Fig. 2. Velocity vector field coloured by velocity magnitude for mean velocity of 4 m/s.

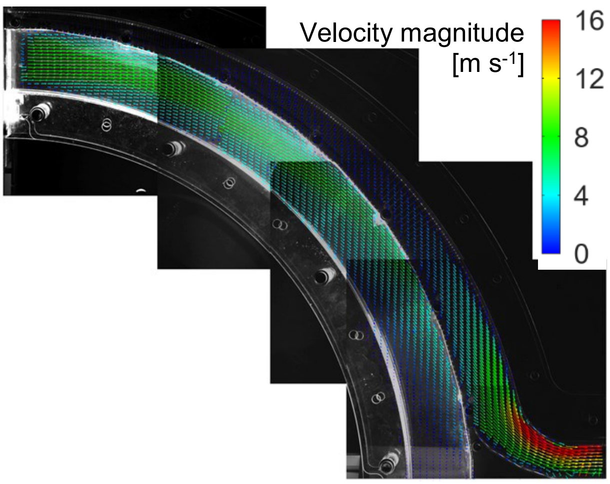

Fig. 3. Velocity vector field coloured by velocity magnitude for mean velocity of 5.7 m/s.

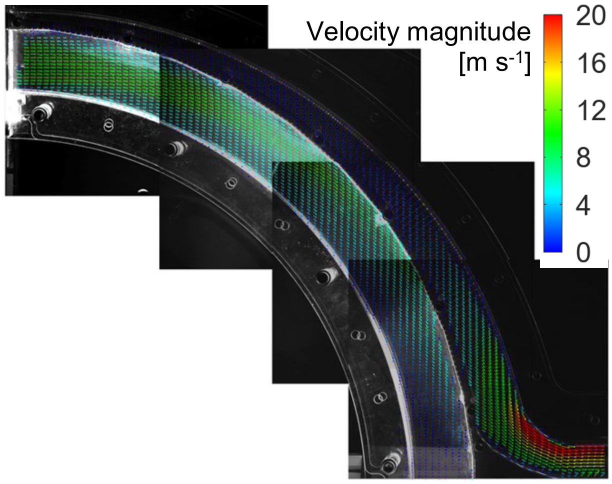

Fig. 4. Velocity vector field coloured by velocity magnitude for mean velocity of 7 m/s.

At the end of the perforated plate, the velocity is turning significantly more in the radial direction of the curve than anywhere else in the perforated plate region. Whereas the change in velocity magnitude in the perforated plate region does not change significantly, the volume flow rate through the plate is clearly highest at the perforated plate end.

4 Porous zone model

The air flow through the observed area was simulated by the CFD software ANSYS Fluent with the *k*-*ω* SST turbulence model. In numerical, studies the porous zone model is suitable for perforated plate simulations. Using the porous model a new source term is added in the momentum equation, [6]:

$$S_i = -\left(\sum_{j=1}^{3} D_{ij}\mu v_j + \sum_{j=1}^{3} C_{ij}\frac{1}{2}\rho|\boldsymbol{v}|v_j\right), \tag{1}$$

where S_i is the source term in coordinate direction i, $\boldsymbol{v}$ is velocity vector, v_i is velocity vector component in direction i, ρ is density, μ is dynamic viscosity and $\boldsymbol{D}$ and $\boldsymbol{C}$ are prescribed matrices of viscous loss coefficients D_{ij} and inertial loss coefficients C_{ij}. Appropriately the first term on the right-hand side of equation (1) represents viscous loss and comes out of Darcy's law and the second term on the right-hand side of equation (1) is inertial loss term. In equation (1) viscous and inertial loss coefficients are the only variables defining the porous zone properties.

4.1 Momentum source term

Various options are open on how to obtain perforated plate viscous and inertial loss coefficients for the momentum source term in the porous zone model. In this study, two different methods are used. First, the coefficients are obtained from an empirical equation, second, they are calculated by regression of pressure drop and velocity from the numerical simulation of normal flow through the defined perforated plate.

4.1.1 Empirical expression

The empirical expression presented by Kast [5] where the inertial loss coefficient in the normal direction is defined in terms of perforated plate porosity ϕ, thickness L, hydraulic (hole) diameter d_h and resistance coefficient k as follows

$$C_n = \frac{k}{\phi^2 L} \; ; \quad \frac{L}{d_h} \gg 0. \tag{2}$$

The porosity of the used perforated plate is $\phi = 0.3715$ and thickness is $L = 1.4$ mm. In terms of porosity and discharge coefficient

$$\alpha = 0.6 + 0.4\,\phi^2, \tag{3}$$

resistance coefficient is given for $\frac{L}{d_h} \gg 0$:

$$k = \left(\frac{1}{\alpha} - 1\right)^2 + (1-\phi)^2. \tag{4}$$

Thus, the inertial loss coefficient is fully defined. For this method, the viscous loss coefficient is set to 0.

4.1.2 Numerical data regression

For the second method, an air flow normal to the perforated plate in a square channel with periodic (or symmetry) boundaries in place of channel walls was simulated. For various mean flow velocities v_∞ at the channel inlet, the pressure drop ΔP between inlet and outlet was monitored. Further second-order regression curve was evaluated for the pressure-velocity data

$$\Delta P = -S_n L = l_n v_\infty + q_n v_\infty^2. \tag{5}$$

Using equation (1) viscous loss term in the normal direction D_n and inertial loss term in the normal direction C_n were calculated from linear coefficient l_n and quadratic coefficient q_n in equation (6) respectively.

Since the perforated plate used for experimental investigation is varnished the round holes in the plate are expected not to having sharp edges. To cover the possible case with sharp holes edges, two different geometries of perforation were used for the numerical data regression. One with simple sharp holes edges and the other with the edges rounded by the radius of 2 mm. The pressure-velocity data and regression curves for both cases are shown in Fig 5.

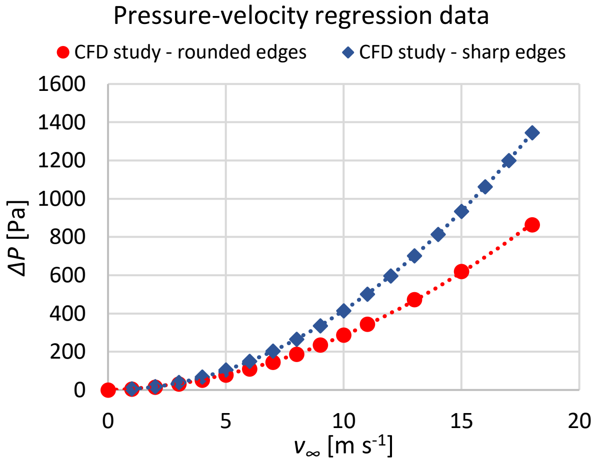

Fig. 5. Pressure drop ΔP on mean velocity v_∞ for normal air flow through perforated plate with sharp and round edged holes.

4.1.3 Tangential direction resistance coefficients

From the two above-described methods three sets of inertial and viscous loss coefficients in the normal direction to the perforated plate are evaluated, Table 1. For a proper numerical description of the porous zone, coefficients in the plate tangential direction should be used. Assuming the flow will not pass through the closed surface the tangential resistance should be higher than normal. Based on Oezcan [7] the coefficients in tangential direction were determined 10 times higher than in normal one. Thus, the porous zone model is fully defined in the local coordinate system associated with the perforated plate.

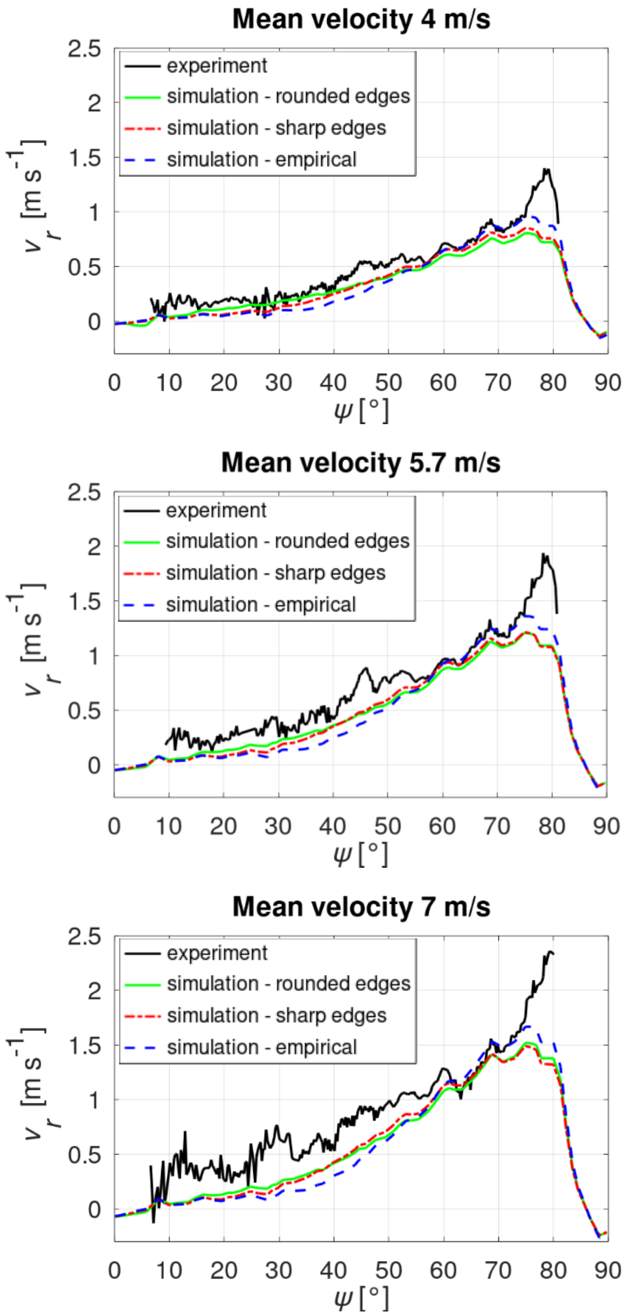

Fig. 6. Radial velocity 15 mm below the plate.

Table 1. Evaluated inertial and viscous loss coefficients in the direction normal to the plate from different methods.

	C_n [m^{-1}]	D_n [m^{-2}]
Empirical expression method	3478.80647	0
Regression method – sharp edges	4836.61808	3500394.63
Regression method – rounded edges	3059.70845	96811365.4

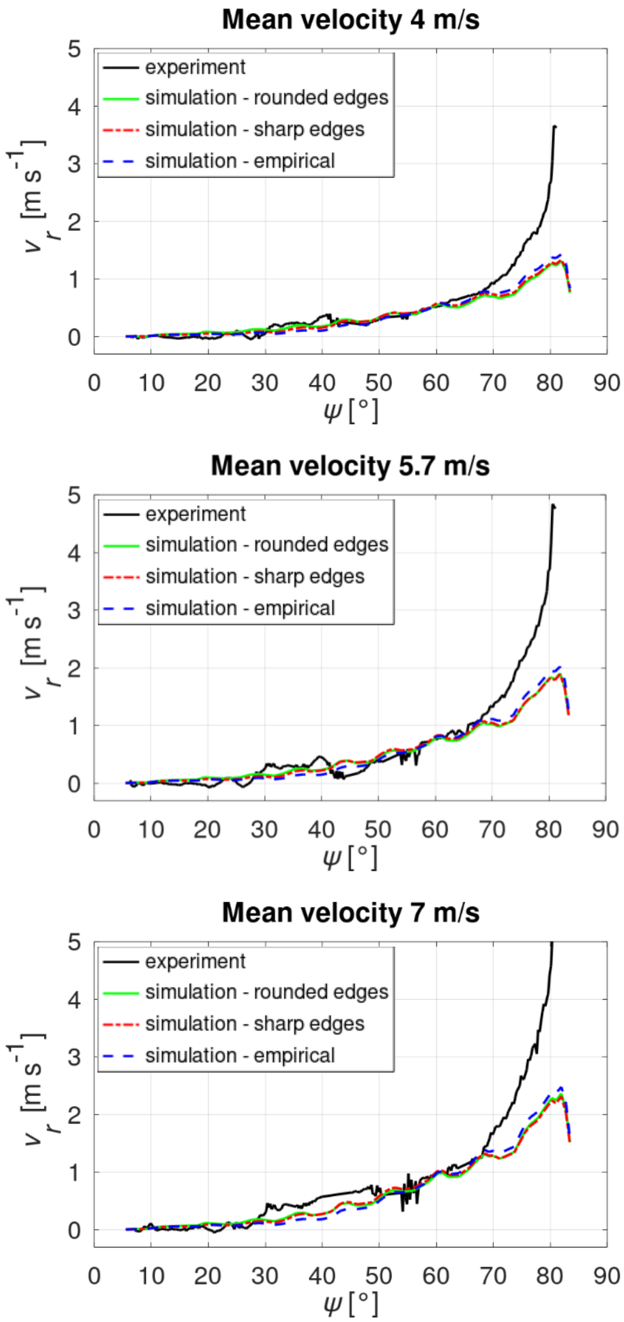

Fig. 7. Radial velocity 20 mm above the plate.

5 Numerical results

Simulations of air flow through the curved perforated plate were performed with the geometry and boundary conditions from the PIV measurements. Overall, three different mean (inlet) velocities 4 m/s, 5.7 m/s and 7 m/s and three different sets of porous zone coefficients (see Table 1) were used. Radial (normal to the perforated plate) and tangential velocity components to the channel curve were monitored 20 mm above and 15 mm below the plate.

Comparison of numerical and experimental results, for radial and tangential velocity components below and above the perforated plate, is shown for the mean velocity of 4 m/s, 5.7 m/s and 7 m/s in the Fig. 6 - Fig 9. The velocity is displayed depending on the angular coordinate ψ withthe origin at the beginning of the channel curve.

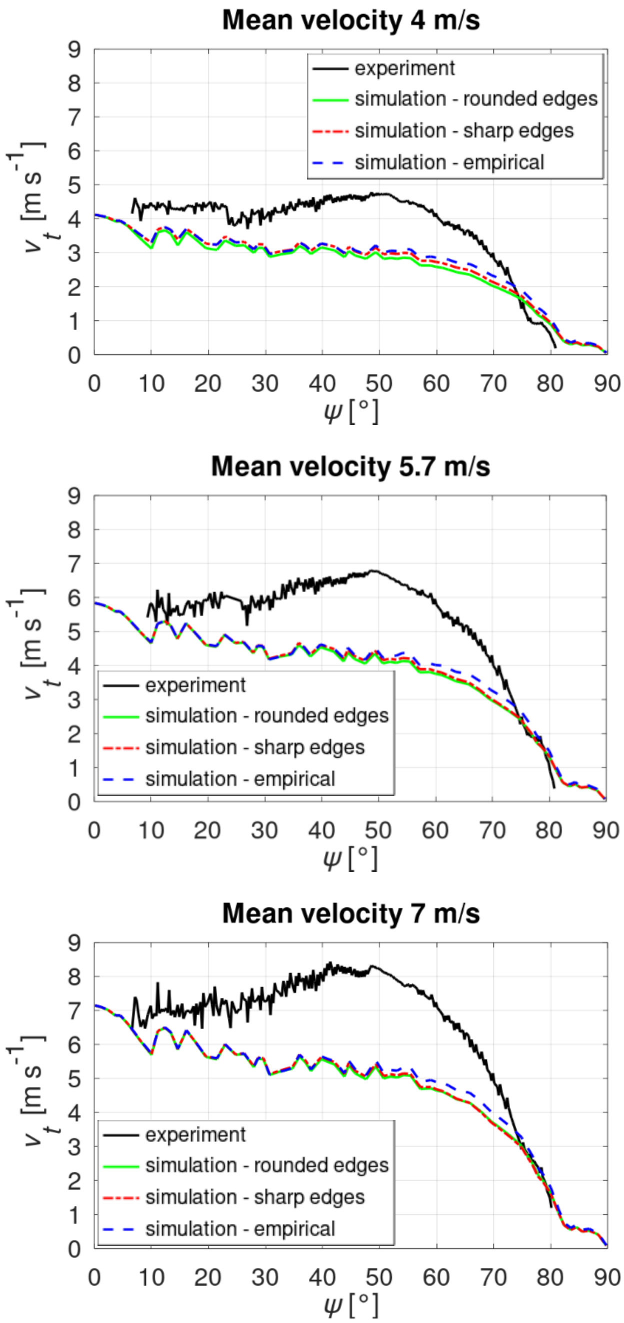

Fig. 8. Tangential velocity 15 mm below the plate.

https://doi.org/10.1051/epjconf/202226401015

The results show consistency for all used porous zone coefficient evaluation methods. The tangential velocity above the perforated plate, Fig. 9, shows a good agreement with the PIV experiment. The radial velocity below the plate in the Fig. 6 shows also a good agreement for the radial velocity component.

The experimental results for the radial velocity component above the perforated plate in Fig. 7, shows a peak at the end of the plate, which is significantly higher in comparison with the numerical results. There is a high chance that the difference is caused by measurement inaccuracy. In Fig. 8, the tangential velocity component below the perforated plate differs distinctly between simulation and experiment. The simplification of the porous model approach has probably the most influence here alongside the measurement inaccuracy.

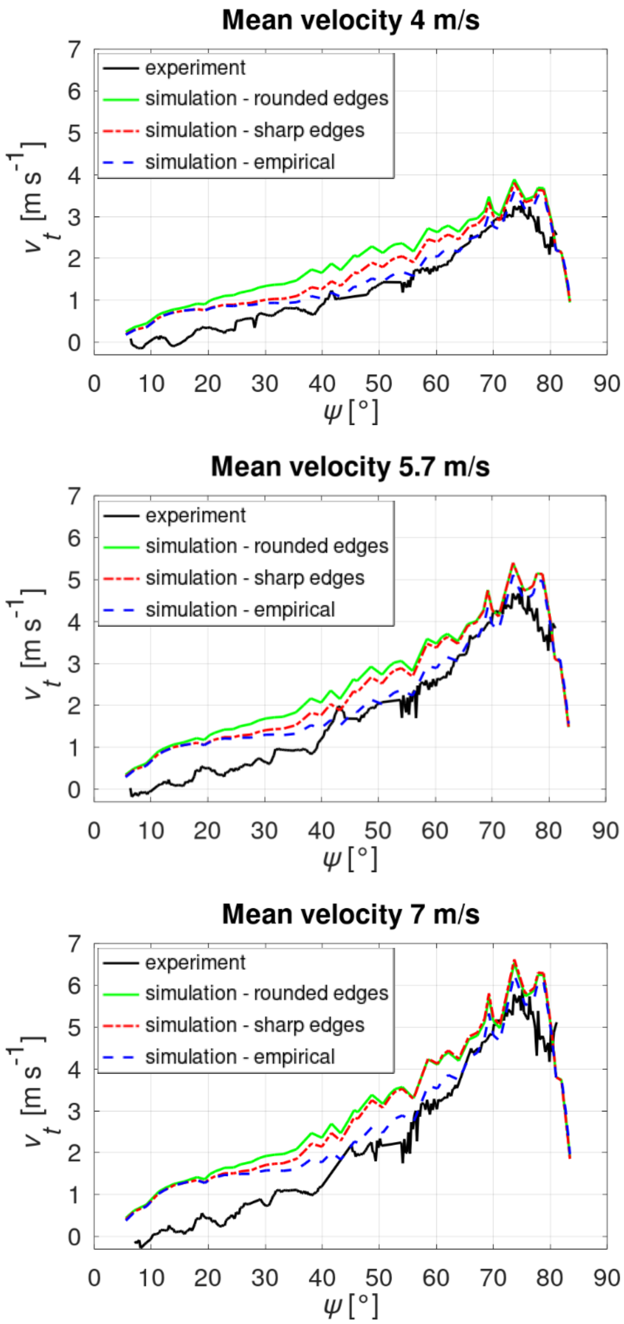

Fig. 9. Tangential velocity 20 mm above the plate.

6 Selected methods limitation

The definition of inertial and viscous loss coefficients by Oezcan [7] implies that the coefficients in the tangential direction should be higher, than in the normal direction. But there is no exact specification of how much higher they should be. It can differ based on $\frac{L}{d_h}$ ratio of the perforated plate. For the first simulations, the tangential coefficients were set 10 times higher than normal related by the example presented by Oezcan [7]. The resulting normal and tangential velocities below and above the plate are shown in Fig. 11. As a reference case, the mean velocity of 7 m/s and empirical porous zone coefficients were tested.

The numerical results in Fig. 10 are strongly dependent on porous zone tangential coefficients value and they are most consistent with the experimental results in the case of tangential coefficients 10 times higher than ones in the normal direction. It means that with the used perforated plate geometry, 10 times higher porous zone coefficients in the tangential direction (than in the normal direction) are the most sufficient, but with some other perforated plate geometries, it presumably would not be so.

To determine if there is a more appropriate way to define tangential porous zone coefficients a short study of pressure drop dependency on an air flow impact angle was carried out. A flat perforated plate geometry was used in an air flow with the mean flow velocity of 7 m/s and compared with the porous zone model with tangential coefficients 10 times higher than normal. The impact angle varied from 0° to 80° from normal with an increment of 10°.

The resulting pressure drop was consistent for the perforated plate and porous zone. But it was observed, that the porous zone redirects the air flow significantly more to the zone (or the plate) normal direction than the perforated plate. The flow redirection comparison of the perforated plate with rounded holes edges and the porous zone (coefficients from round edges regression) is shown in Fig. 10 for impact angle 40° from normal. It reveals that concerning the air flow velocity direction, the porous zone coefficients in the tangential direction should be lower.

The results of the study disagree with the original definition of the porous zone tangential coefficients. It suggests that tangential coefficients should be not only lower than normal coefficients but even that they should

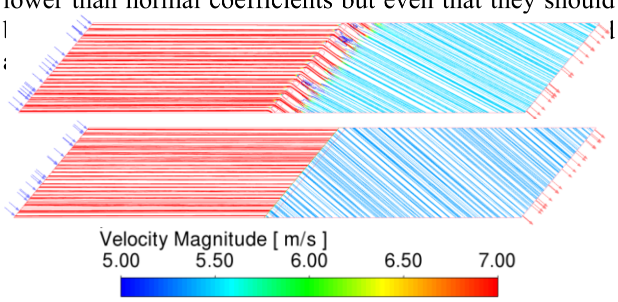

Fig. 10. Streamlines of air flow through perforated plate (top) and porous zone (bottom) coloured by pressure - impact angle 40°.

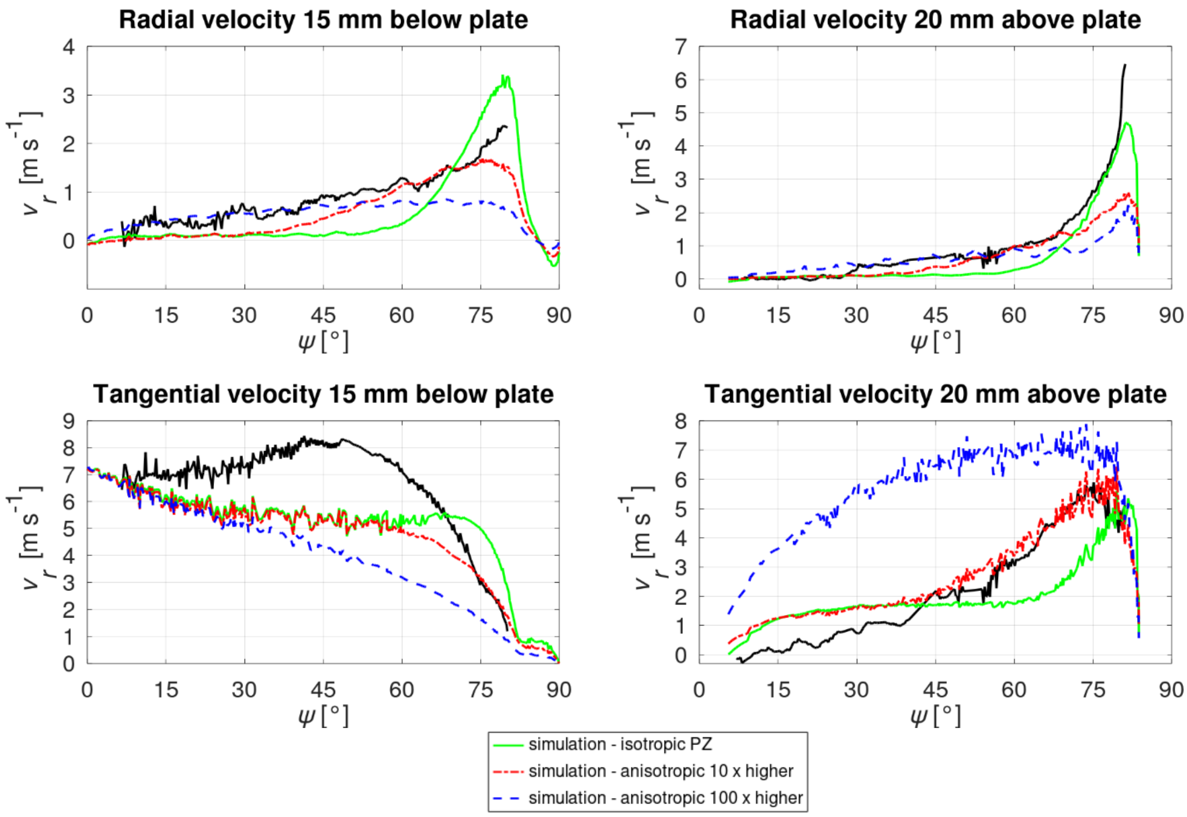

Fig. 11. Radial and tangential velocity for mean velocity 7m/s and empirical method porous zone coefficients.

7 Conclusion

Air flow through the curved perforated plate was investigated in this study. The first part was devoted to the experimental measurements of the flow velocity using the PIV method. Vector velocity fields were shown for three different air flow mean velocities.

Further porous zone model was employed to represent perforated plate in simulations. Three different sets of porous zone inertial and viscous loss coefficients were evaluated using two different methods. Normal and tangential velocities 15 mm below and 20 mm above the plate were compared for experimental results and numerical results with various porous zone coefficients.

The comparison showed satisfactory agreement between the experiment and simulation. But there are several deficiencies of the porous zone, especially in the used resistance coefficients evaluation methods. All the used methods are based on the porous zone coefficients definition in the direction normal to the perforated plate but do not explicitly define the coefficients in the tangential direction. For the investigated case of curved perforated plate, the most suitable porous zone coefficients in the plate tangential direction are 10 times higher than in the normal direction. So defined model performs well with the perforated plate normal to the flow, but not so well with an acute angle between the plate and the flow direction. It was shown, comparing perforated plate simulation with porous zone simulation for acute impact angle, that the flow is more redirected by the porous zone than by the perforated plate. For more corresponding results the porous zone coefficients in tangential direction should be set lower than they are. In a most precise definition, the viscous and inertial loss coefficients would presumably be functions of air flow impact angle on the plate and the mean flow velocity. This should be considered when using the porous zone substitution for perforated plate and might be a subject for further studies.

Acknowledgement

This publication was written at VÚTS, a.s. with the support of the project FV40025. Our acknowledgement belongs to all donors that helped us to reach the results of the work.

References

1. D. Allori, G. Bartoli, A. F. Miguel, Int. J. Fluid Mech. Res., 39, 136-148 (2012)
2. P. Tanner, J. Gorman, E. Sparrow, Int. J. Numer Method H., 29, 4310-4333 (2019)
3. A. F. Miguel, J. Porous Media, 22, 1439-1448 (2019)
4. I. E Idelchik, Handbook of hydraulic resistance, third edition, CRC Press Inc., Boca Raton, US (1960)
5. W. Kast, E.S. Gaddis, K. E.Wirth, J. Stichlmair, L1 Pressure Drop in Single-Phase Flow. VDI-Buch. Springer, Berlin, Heidelberg (2010)
6. Ansys® Fluent, Ansys Fluent User's Guide, 2021 R2, 1206-1242 (2021)
7. M. Oezcan, How to Use the Porous Media Feature to Define a Perforated Plate, SimScale (2020) https://www.simscale.com/