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Fundamental study on flow-deflector performance for diffuser

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Abstract. Diffusers or diverging pipes/ducts are extensively used in many industrial aspects. So, diffusers with high efficiency are desired under both spatial and cost's limitations. In our previous studies [Hirata et al., 2006 and 2008], we proposed a flow deflector inside the diffuser-part of an automotive catalytic converter, in order to reduce energy loss and to improve thermal uniformity. In this study, we experimentally and numerically investigate the influence of the downstream substrate upon the effectiveness, using a conical diffuser. As a result, it is revealed that the flow deflector is effective for diffusers as well as catalytic converters. By computation which agree with experiment, we have shown the flow inside the diffuser with the flow deflector.

1. Introduction

Diffusers or diverging pipes/ducts are extensively used in many industrial aspects. So, various studies relating to the diffuser's area ratio, angle, length, existence/non-existence of the outlet pipe and shape of cross section have been conducted. (See [1-5] for pressure loss, [6-10] for flow visualisation and [11, 12] for pressure-loss reduction by flow-separation control.) In consequence of these studies, it is commonly known that the most efficient diffuser is with very-large streamwise length and with the cross section which is gradually widen at an expanding angle of 5 to 10 degree.

However, diffusers with a small streamwise length and a large expanding angle has been often used because of spatial and cost's limitations. An example is the automotive catalytic converter [13-21]. So, diffusers with high efficiency are desired under both spatial and cost's limitations.

In our previous studies [16, 17, 20, 21], we proposed a flow deflector inside the diffuser-part of an automotive catalytic converter, in order to reduce energy loss and to improve thermal uniformity. We may expect the effectiveness of the flow deflector not only for catalytic converters but also for general diffusers without any catalytic substrates in their downstreams. Then, in this study, we attempt to investigate the influence of the downstream substrate upon the effectiveness, using a conical diffuser, experimentally and numerically.

2. Experiment method

2.1. Model: conical diffuser with flow deflector

Figure 1 shows the schematic diagram of the axial model, that is to say, a catalytic converter equipped with a (solid-dome) flow deflector inside the conical diffuser of the catalytic converter. More specifically, figure (a) denotes an overview. Figures (b) and (c) denote the detail and the cross-section view of a dome-shape flow deflector with solid structure (a solid-dome flow deflector), respectively.

The (solid-dome) flow deflector is designed as the effective cross-section area A_e linearly increases from A_o to $(A_e)_{do\text{-}end}$ in the flow direction. Furthermore, the cross-section area A_h of the centre hole is designed to increase linearly from $(A_h)_o$ to $(A_h)_{do\text{-}end}$ in the flow direction. So, the diameter of the flow-deflector outer boundary is defined by

$$\Phi_{do}^{*} = \frac{\sqrt{x^{*}}}{L_{di}^{*}}\sqrt{(\Phi_{di\text{-}end}{}^{*}-1)x^{*} + 2L_{di}{}^{*}(\Phi_{di\text{-}end}{}^{*}-1) + \frac{\left(L_{di}^{*}\Phi_{h}^{*}\right)^{2}}{x^{*}} - (L_{di}{}^{*})^{2}\frac{dA_{e}{}^{*}}{dx^{*}}}\ . \tag{1}$$

And, the diameter of the flow-deflector centre hole is defined by

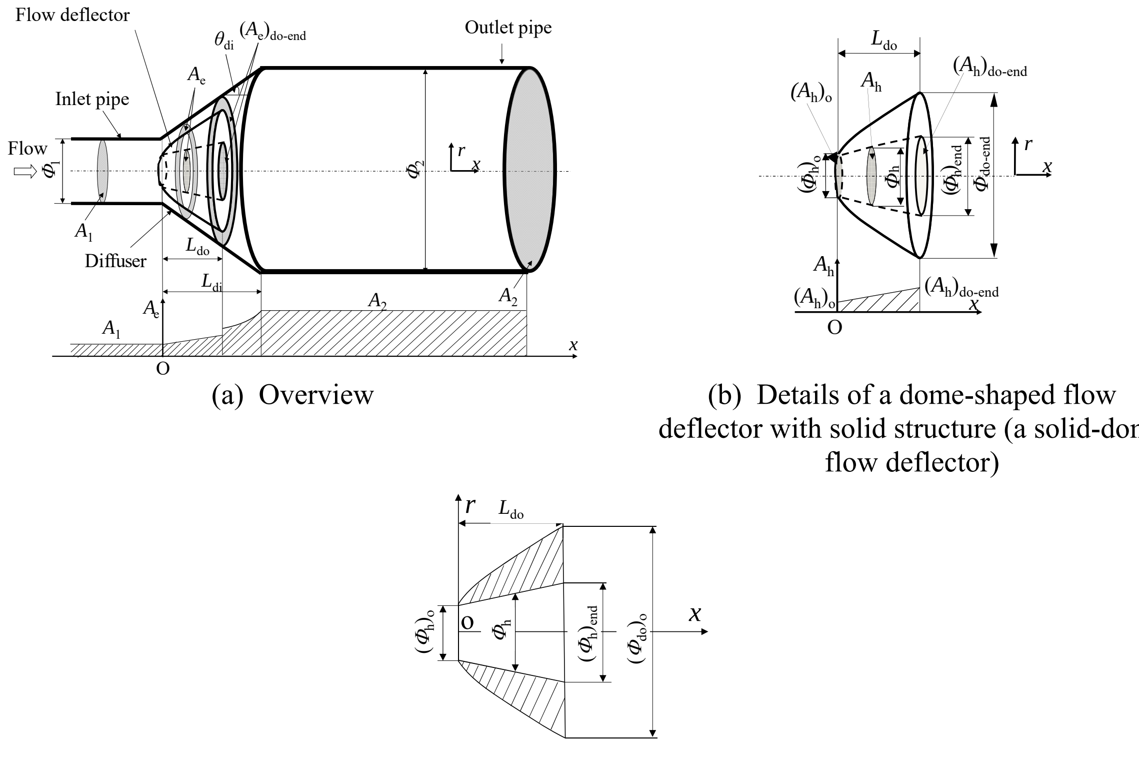
$$\Phi_h{}^{*} = \sqrt{((\Phi_h)_o{}^{*})^{2} + \frac{dA_h{}^{*}}{dx^{*}}x^{*}}\ . \tag{2}$$

We should note that all physical quantities with an asterisk '*' as their superscript are normalised ones. Table 1 summarises the experimental parameters of the conical diffuser with the flow deflector, together with their tested values in the present study. The values of the experimental parameter are obtained as optimised ones in our previous studies [16, 17].

2.2. Pressure Loss and Flow Uniformity

Pressure is normalised by the dynamic pressure at the origin. Then, non-dimensional form of the pressure loss ΔP of a diffuser is given by

$$\Delta P^{*} = \frac{\Delta P}{\rho V_o{}^{2}/2}\ . \tag{3}$$



(a) Overview

(b) Details of a dome-shaped flow deflector with solid structure (a solid-dome flow deflector)

(c) Cross-section view of a dome-shaped flow deflector with solid structure (a solid-dome flow deflector)

Figure 1. Axial model: a conical diffuser with a flow deflector.

As an indicator for flow uniformity, we introduce a flow-uniformity factor γ, whose definition is as follows.

$$\gamma = 1 - \frac{1}{2n}\sum_{i=1}^{n}\sqrt{\frac{(v_i - V_{out})^2}{V_{out}^2}\left(\frac{r_i}{\Phi_{sub}/2}\right)^2}\text{, with } V_{out} = \frac{4Q_{out}}{\pi \Phi_{sub}^2}, \tag{4}$$

where Φ_{sub} is equal to Φ_{out}. The composite velocity v_i represents that at a position r_i, and n is the total number of data.

2.3. Experimental apparatus

As an example, Figure 2 shows the present experimental apparatus for the measurement of the pressure loss of the conical diffuser with the flow deflector. Working fluid is air with a constant room temperature, which is almost the same everywhere in the experimental apparatus. The air is driven by a blower (No. 1) into a flow conditioner (No. 3) which is a long and straight inlet pipe with length L_{in} and diameter Φ_{in} (= Φ_o). The inlet pipe is connected to a diffuser (No. 4), and a long-and-straight outlet pipe (No. 5) at its downstream end. Velocity and pressure are simultaneously detected by a hot-wire anemometer (No. 6) and two pressure transducers (No. 7), whose signals are store and analysed by a PC (No. 8).

For the improvement of catalytic-conversion performance, we consider the velocity profile, which is the ensemble of spatially-averaged velocities for small channel cells of the monolith substrate to be exact. So, we should measure the velocity profile just near the upstream or downstream of the substrate. However, because such measurements are accompanied by practical difficulties, we observe the velocity profiles at the cross section of 205 mm downstream from the substrate, that is, at x = 295 mm (x/Φ_1 = 11.4).

2.4. Computational procedure

Computation is carried out using open-source software OpenFOAM in version 2.3.0. The overview of numerical set-up is summarised in Table 2. The analised model is acane-shaped flow deflector with solid structure (a solid-cone flow deflector), which is close to the experimental model (a solid-dome flow deflector). The mesh consists of 101000 hexahedral and pentahedral cells. The pentahedral cell are used only in the centre region. The computational domain covers the inlet pipe, the diffuser and the outlet pipe which does not include the substrate, as the present computation is not in DSC but only ODC. The k-ε turbulence model is used and velocity inlet with pressure outlet is prescribed for boundary conditions.

Table 1. Experimental parameters of a conical diffuser with a flow deflector.

Φ_1 [m]	2.6×10^{-2}
Φ_2 [m]	8.2×10^{-2}
L_{di} [m]	4.0×10^{-2}
L_{do} [m]	3.0×10^{-2}
$(\Phi_h)_o$ [m]	1.5×10^{-2}
$(\Phi_h)_{end}$ [m]	2.0×10^{-2}
$(\Phi_{do})_{end}$ [m]	5.9×10^{-2}
$2\theta_{di}$ [°]	70
V_1 [m/s]	5.51–58.6
Re	9.9×10–9.8×10^4

3. Results and discussion

To begin with the validation of static-pressure measurements, we conduct a preliminary experiment concerning the uncertainty using a long straight pipe. Figure 3 shows the streamwise distribution of a static pressure, together with the Darcy-Weisbach equation with a Blasius' pipe-friction coefficient

$$\lambda = 0.3164Re^{-1/4} \tag{5}$$

which is effective in a range of $Re = 3.0\times10^3 - 1.0\times10^5$ (Weisbach, 1845; Blasius, 1913). The origin of the streamwise coordinate x is enough downstreram from the pipe's inlet to appear a linearly-decaying static pressure with a fully-developed radial velocity profile. We can confirm that the present measurement coincides with the equation with good reproductivity.

3.1. Pressure-loss coefficient by experiment

Figure 4 shows the pressure-loss coefficient ζ of the conical diffuser plotted again *Re,* in such two cases as (1) an ordinary-diffuser case ODC without any downstream substrate and (2) a downstream-substrate case DSC. For reference, the figure also shows ζ by Rend et al. (2013) and by Hirata et al. (2008). The former concerns the ODC with small θs. And, the latter concerns the catalytic converter whose diffuser part has the same dimensions as the present model and whose substrate is shorter than the present model. In the later, we assume 0.3 as the pressure-loss coefficient of the contraction part, when we specify ζ form ΔP^* in Hirata et al. (2008).

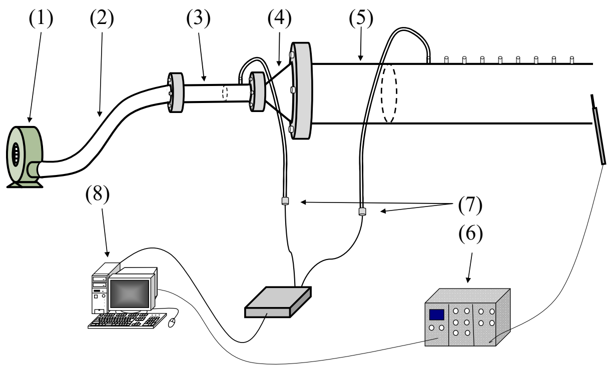


Figure 2. Experimental apparatus for pressure measurement of a conical diffuser with a flow deflector. (1) Blower, (2) flexible hose, (3) inlet pipe, (4) diffuser, (5) outlet pipe, (6) hot-wire anemometer, (7) pressure transducers and (8) PC.

Table 2. Numerical set-up.

Turbulence model	k-ε
Pressure-velocity coupling	PISO
Discretization schemes	
Time	Euler
Gradients	Gauss linear
Laplacian Schemes	Linear, corrected
Interpolation	Linear
Boundary conditions	
Inlet	Velocity inlet with fixed velocity Values of k and ε correspond to 5% of turbulence intensity
Outlet	Pressure outlet with fixed value of kinematic pressure $p/\rho = 0$

At first, we consider the DSC. At $Re \gtrsim 4\times10^4$, ζ without any flow deflector is constant to 0.8 being independent of *Re*. This well corresponds to Hirata et al. (2008). At $Re \lesssim 4\times10^4$, ζ without any flow deflector increases with decreasing *Re*, while that by Hirata et al. gradually decreases with decreasing *Re*. On the other hand, at $Re \gtrsim 4\times10^4$, ζ with a flow deflector is constant to 0.6 being independent at *Re*. This well corresponds to Hirata et al., as well. At $Re \lesssim 4\times10^4$, ζ with a flow deflect increases with decreasing *Re*, while that by Hirata et al. gradually decreases with *Re*. In summary, we can confirm good accuracy because of the agreement between the present result in the DSC and Hirata et al. (2003) expect for low $Re \lesssim 4\times10^4$. And, the flow deflector can achieve more than 20% reduction on ζ.

Next, we consider the ODC. At $Re \gtrsim 4\times10^4$, ζ without any flow deflector is constant to 0.8 being independent of *Re*, as well as the DSC and Hirata et al. At $Re \lesssim 4\times10^4$, ζ without any flow deflector gradually decreases with decreasing *Re*, as well as not the DSC but Hirata et al. On the other hand, at $Re \gtrsim 4\times10^4$, ζ with a flow deflector is constant to 0.6 being independent of *Re*, as well as the DSC and Hirata et al. At $Re \lesssim 4\times10^4$, ζ with a flow deflector gradually decreases with decreasing *Re*, as well as not the DSC but Hirata et al., again. In summary, the flow deflector can achieve more than 20% reduction on ζ, as well as the DSC and Hirata et al.

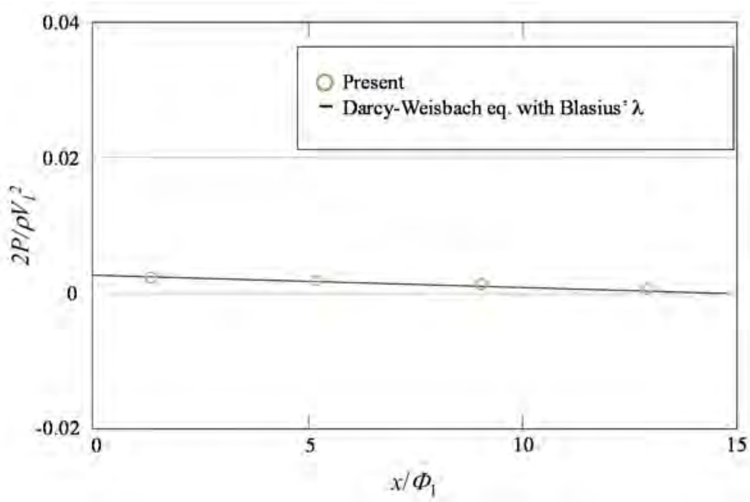


Figure 3. Streamwise distribution of static pressure p for a straight long pipe (at $Re = 2.1\times10^4$ and $Re_f = 0$).

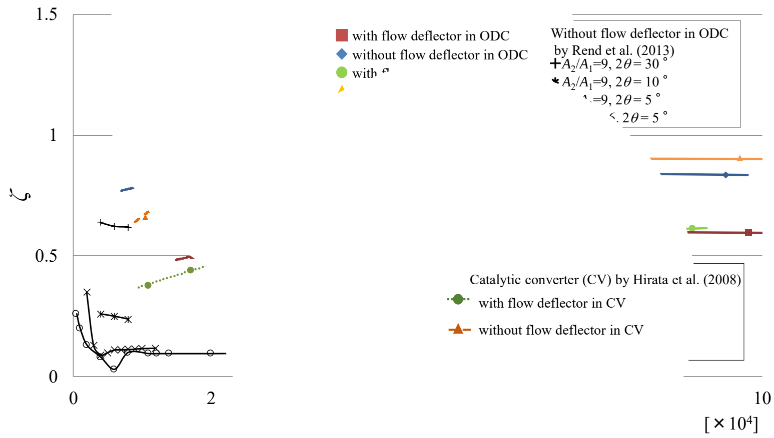


Figure 4. Pressure-loss coefficient ζ of a conical diffuser versus *Re*, in such two cases as (1) an ordinary-diffuser case ODC and (2) a downstream-substrate case DSC.

To conclude, we can confirm that the influence of the flow deflector is remarkable; at $Re \gtrsim 4\times10^4$, the reduction on ζ is more than 20% even in the ODC, as well as the DSC and Hirata et al. On the other hand, at $Re \lesssim 4\times10^4$, we cannot ignore the influence of Re upon ζ, which seems complicated and should be solved in future. Above high performance of a flow deflector at such high Re as more than 4×10^4 implies the effective suppression of flow separation by the flow deflector.

3.2. Flow-uniformity factor by experiment

In order to confirm the improvement in the velocity profile by a flow deflector, hot-wire measurements of the time-mean velocity are summarised in Table 3 as the flow-uniformity factor γ in the downstream of the conical diffuser (at $x/\Phi_1 = 11.4$). We can see that γ achieves approximately 90% in all cases regardless of a flow deflector, at both high and low *Re*s. The value represents γ at high *Re*, while the value in parentheses represents γ at low *Re*. In summary, flow uniformity is in high level in all the cases with/without flow deflector in a somewhat downstream of a diffuser, owing to turbulent flow. Such constant high-level uniformity is contrast to the case of a catalytic converter where its downstream dimension is restricted.

3.3. Computation and Flow visualisation by computation

Figure 5 shows the comparison between computation and experiment, which are the flow distributions with a flow deflector in the ODC at $Re = 5.0\times10^4$ and $x = 296$ mm. The computation shows good agreement with the experiment, although the computational accuracy should be improved more in future including other cases.

Table 3. Flow-uniformity factor γ of a conical diffuser (at $x/\Phi_1 = 11.4$).

(1) Ordinary-diffuser case (ODC)	With flow deflector	0.93 at $Re = 6.3\times10^4$ (0.88 at $Re = 1.8\times10^4$)
	Without flow deflector	0.97 at $Re = 7.1\times10^4$ (0.95 at $Re = 1.6\times10^4$)
(2) Downstream-substrate case (DSC)	With flow deflector	0.90 at $Re = 6.8\times10^4$ (0.96 at $Re = 1.0\times10^4$)
	Without flow deflector	0.86 at $Re = 6.2\times10^4$ (0.95 at $Re = 1.1\times10^4$)

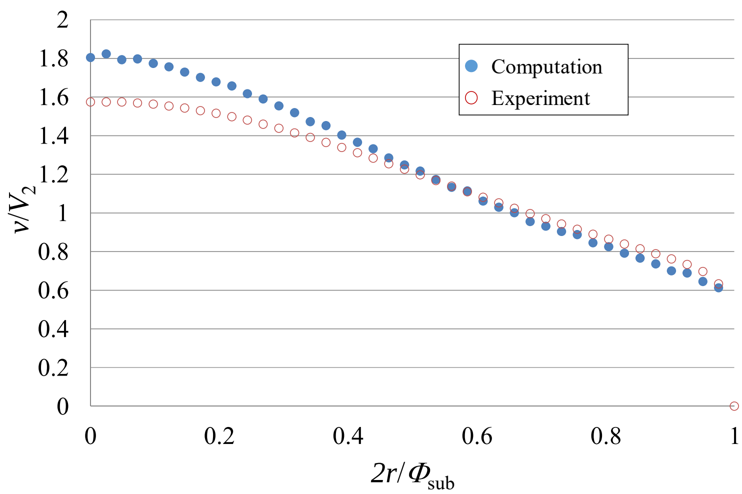


Figure 5. Comparison between computation and experiment: flow distribution (with flow deflector in ODC, at $Re = 5.0\times10^4$ and $x = 296$ mm).

Figures 6 and 7 show a typical flow field obtained by computation, namely, time-mean distributions of velocity vectors (in Figure 6) and static pressure (in Figure 7) with the flow deflector in the ODC inside the diffuser on a center plane at $Re = 5.0{\times}10^4$. It is confirmed that the flow is axi-symmetric even in the downstream, but might be with turbulent perturbations in actual instantaneous flow. Especially in Figure 6, we can see a strong annular streaming without flow separation near the walls of the diffuser, in addition to the main streaming (or a jet from the centre hole of the flow deflector) at the centre. Such a possibility of computations effectiveness suggests further understanding of flow future researches.

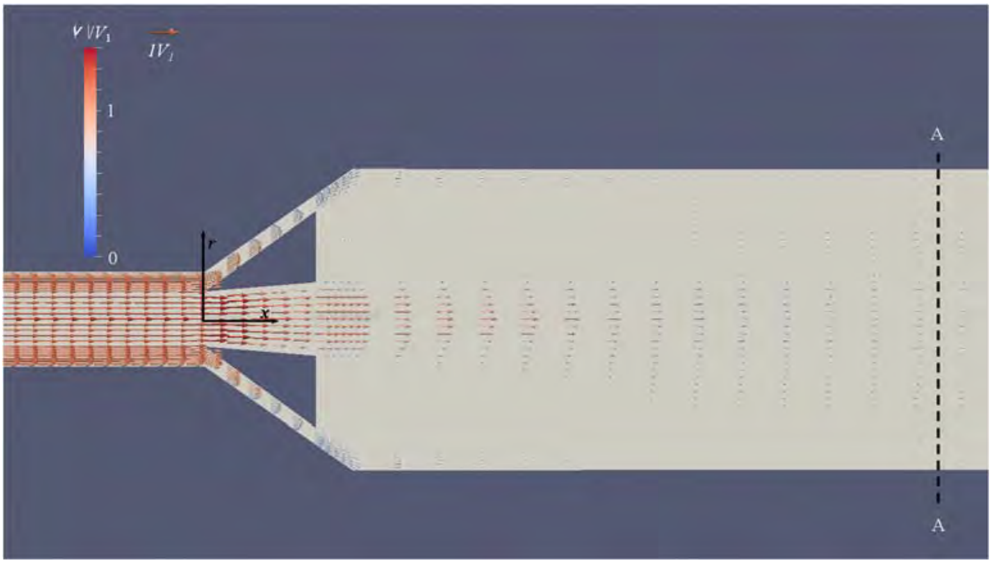


Figure 6. Velocity vectors by computation (with flow deflector in ODC, at $Re = 5.0{\times}10^4$). A-A, at x = 296 mm.

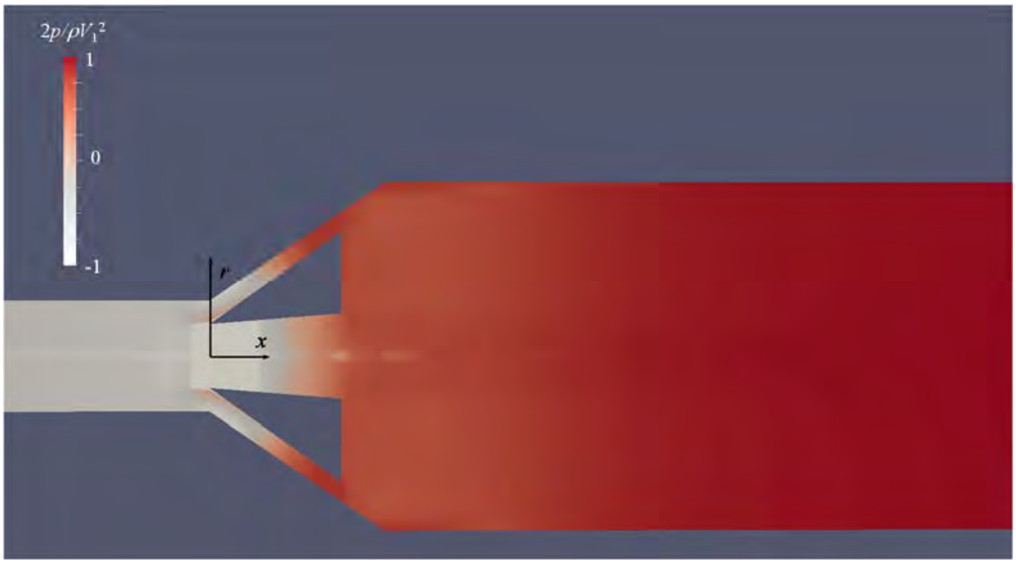


Figure 7. Pressure distribution by computation (with flow deflector in ODC, at $Re = 5.0{\times}10^4$).

4. Conclusion

Expecting the effectiveness of the flow deflector not only for catalytic converters but also for general diffusers without any catalytic substrates in their downstreams, we have experimentally and numerically researched the influence of the downstream substrate upon the effectiveness, using a conical diffuser. Furthermore, we have conducted computations. As a result, it is revealed that the flow deflector is effective for diffusers as well as catalytic converters. By computation which agree with experiment, we have shown the flow inside the diffuser with the flow deflector.

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