Pipe flow pattern downstream of local restrictions studied by an optical method

V M Molochnikov\textsuperscript{1,2}, D V Kratirov\textsuperscript{2}, A N Mikheev\textsuperscript{2}

\textsuperscript{1} Kazan Scientific Center of RAS, Kazan, 420111, Russia
\textsuperscript{2} Kazan National Research Technical University named after A.N.Tupolev, Kazan, 420111, Russia
e-mail: vmolochnikov@mail.ru

Abstract. An approach to the study of gas flow patterns in circular pipes using 2D methods (PIV, SIV) has been proposed. The approach is based on a special device which is similar to a closed test section of a wind tunnel. It allows measurements of flow parameters downstream of local flow restrictions in circular channels without any optical distortions caused by curved pipe walls. The test results are submitted together with some data on the flow pattern downstream of a gate valve at different channel blockage ratios.

1. Introduction

Flow ducts (channels) of power plants are complex systems with a large number of local flow restrictions (control valves, gates), bends, branch pipes, etc. These elements can significantly influence the channel flow pattern (velocity profile distortion, swirl, shedding of vortices of different scales). Such alteration often drastically changes the operation of individual elements of a power plant and the plant on the whole. For example, the velocity profile non-uniformity, flow swirling and vortex shedding from local restrictions can lead to further uncertainty or fluid flow metering system failures \cite{1, 2}. To minimize the effect of local restrictions, special devices like straightening vanes and flow conditioners are often used. However, when their performance is estimated, the turbulent and vortex pattern of flow downstream of these devices is usually not studied.

In this context, when designing power engineering equipment and measurement systems, it is important to be able to estimate the flow pattern at the outlet of different devices, including the one downstream of local flow restrictions of different types. The application of numerical methods and software to computation of a large number of flow regimes in the ducts of complex geometry is very time-consuming and needs further detailed testing. Thus, a laboratory experiment seems to be the most reasonable approach to this problem.

The rapidly developing 2D optical methods of flow pattern investigation (PIV, PTV, SIV, etc.) offer great opportunities for application of this approach. These methods allow measurements of instantaneous vector fields of velocity and vorticity, from which the information on flow pattern and its evolution can be derived. These methods are based on frame-by-frame processing of photos or videos of tracer particles seeded into the flow. The videos are recorded in a light sheet generated by a
pulse or continuous laser. However, experimental research of circular pipe flows by the optical method of PIV revealed the effect of the channel cross-section shape on the measurement uncertainty. The latter is the most pronounced near the wall, which is one of the most critical regions of flow. A laser beam reflected from a tracer particle travels through a transparent curved channel wall of different thickness depending on the distance from the pipe axis on its way to the lens. Moreover, the incidence angle of the laser beam striking the wall is different depending on the curvature of the latter.

In the case of liquid fluids, the light refraction problem can be solved almost entirely if the pipe section is placed into a tank filled with the same fluid or with the one of similar optical properties and is equipped with a plane transparent wall placed normal to the lens [3-8]. Authors [3] showed that this leads to significant reduction in spatial distortions. When studying the flow of fluid whose refractive index significantly differs from the corresponding index of the pipe material, this engineering solution is no longer valid. Making the walls thinner, one can obviously reduce the negative optical effects [7]. However, this only reduces the distorted area to some extent.

There are two main approaches to measurements of flow parameters in pipes using 2D methods. The first one is introduction of corrections for all statistical characteristics of flow in the region where optical distortions of measurements are observed, including the immediate vicinity of the wall. The corrections are derived from the comparison between the measured velocity profile and the well-known velocity law [9] for a developed pipe flow. Then they are used to correct the rest of the measured flow parameters. This approach can be applied to boundary layer measurements but is inapplicable to complex turbulent flows including the separated ones. Sometimes the velocity fields estimated by an optical method are reconstructed from the known local flow parameters obtained by non-optical methods [9–10]. The second approach includes estimation of optical distortion of flow field linear dimensions using calibration targets with further corrections when processing the measurement results. This approach is rather hard to implement. When 2D methods are used in axisymmetric channels, spurious reflection and flare in the near-wall region influence the measurement results [11]. There have been attempts at solving this problem using special masks applied to the flow images. However, this approach appeared to be ineffective, as the authors [11] failed to obtain reliable velocity fields near the wall of a conical diverging channel.

In the present paper, a special device similar to a wind tunnel test section enclosed in a chamber is proposed for reliable measurements of flow parameters in circular pipes. Such a device (called the Eiffel chamber in Russian literature and hereafter) has become a popular element of wind tunnels [12]. The experimental setup is described in Section 2. Section 3 elaborates on test experiments and measurements of flow pattern downstream of a gate valve.

2. Experimental facilities

2.1. Eiffel chamber

Figure 1 shows the diagram of the Eiffel chamber. It had a cylindrical casing 4 with the inner diameter of 450 mm equipped with a glass window 3. The window allowed recording the flow patterns by a high-speed camera. A transparent slot 5 was cut in the casing sidewall to provide light sheet generation in the considered flow area. A light trap was installed opposite to the slot 5, which prevented the laser beam from reflection to the flow region. The Eiffel chamber had a flange 1, attached to an upstream straight run piping with the considered flow restriction, and a flange 2 attached to a downstream straight-run. The design of flanges 1 and 2 allowed installation of the Eiffel chamber in the measurement section with the diameter of $D = 50 – 300$ mm. Besides, the Eiffel chamber’s casing could be rotated about its axis relative to the flanges. This provided the adjustment of measurement plane with respect to the considered local restriction. General view of the camera is given in figure 2.
Figure 1. Diagram of the Eiffel chamber: 1, 2 – flanges; 3 – window for flow pattern video recording; 4 – casing; 5 – transparent slot

Figure 2. General view of the Eiffel chamber. A laser beam trap is visible in the foreground

The pressure in the Eiffel chamber was approximately equal to the total pressure in the flow downstream of the considered local restriction. Thus, there was almost no jet expansion observed downstream of the chamber’s inlet section. For this reason, the flow pattern downstream of the local restriction was similar to the jet pattern near the chamber inlet. This pattern could be measured, among other regions, in the immediate vicinity of the channel wall.

2.2. Experimental setup and procedure
The experimental setup schematic is shown in figure 3. Flow velocity fields in a smooth pipe and a pipe downstream of local restrictions were studied on this setup. The setup included a straight pipe 1, local restriction in the form of a gate valve simulator 2, the Eiffel chamber 3 installed immediately downstream of the gate valve, and a downstream straight-run pipe 4. The air was sucked through the setup by a fan. The diameter of the pipe in which flow velocity fields were measured was \( D = 150 \) mm. The measurements were performed in two series. The first one was test experiments: velocity profiles were measured in the developed turbulent flow in the circular pipe. No gate valve simulator was installed in this series. Velocity profiles immediately downstream of the gate valve simulator were measured in the second series. The blockage ratio varied in these experiments (25, 50 or 75\% of the pipe cross section was obstructed).

The instantaneous velocity vector fields and the profiles of statistical characteristics of flow derived from the latter were measured by Smoke Image Velocimetry (SIV) technique [13-14]. The technique is based on measurements of displacements of turbulent structures during a fixed time.

Figure 3. Schematic of experimental setup: 1 – straight-run piping; 2 – gate valve; 3 – Eiffel chamber; 4 – downstream straight-run
interval between the frames of a flow visualization video. The flow pattern was recorded using a high-speed monochrome Fastec HiSpec camera in a light sheet generated by a continuous laser. The flow was seeded with tracer particles, i.e. small glycerol droplets suspended in the flow. The particle diameter was 1-5 µm. The tracers were generated by an aerosol generator FOG 2010 Plus installed at the pipe 1 inlet (figure 3).

3. Results and discussion
Test experiments included the velocity profile measurements in the developed turbulent flow in the circular pipe at different Reynolds numbers. To that end, a 6.5-meter long (50 D) straight run circular pipe 1 (figure 3) was installed upstream of the Eiffel chamber without the gate valve 2. An example of flow velocity profile $U_x(y/R)$ is shown in figure 4 for the Reynolds number $Re = 2.06 \times 10^4$ based on the average velocity and pipe diameter.

Here, $R = D/2$. The figure shows good agreement between the velocity profile and the known power law $U_x/U_0 = (y/R)^{1/n}$ [16]. In the region where the law of the wall is applicable, the experimental results agree well with the classical relation $u^+ = 2.5 \ln y^+ + 5.5$ (figure 5). Here, $u^+ = u/u_\tau$, $y^+ = y u_\tau/\nu$; $u_\tau = (\tau_w/\rho)^{0.5}$; $\nu$ is the kinematic viscosity. Wall shear stress $\tau_w$ was estimated according to Clauser [15]. Deviation of $\tau_w$ from its theoretical values for the developed turbulent pipe flow [16] was 2.1%.

Here, $R = D/2$. The figure shows good agreement between the velocity profile and the known power law $U_x/U_0 = (y/R)^{1/n}$ [16]. In the region where the law of the wall is applicable, the experimental results agree well with the classical relation $u^+ = 2.5 \ln y^+ + 5.5$ (figure 5). Here, $u^+ = u/u_\tau$, $y^+ = y u_\tau/\nu$; $u_\tau = (\tau_w/\rho)^{0.5}$; $\nu$ is the kinematic viscosity. Wall shear stress $\tau_w$ was estimated according to Clauser [15]. Deviation of $\tau_w$ from its theoretical values for the developed turbulent pipe flow [16] was 2.1%.

Figure 4. Velocity profile in the pipe: 1 – experiment; 2 – power law [15]

Figure 5. Velocity profile in wall coordinates: 1 – law of the wall [15]; 2 – experiment

Figure 6. Profiles of velocity (a) and its turbulent fluctuations (b) downstream of the gate valve at 25% blockage ratio. Different marks denote repeated series of measurements.
Figure 7. Profiles of velocity (a) and its turbulent fluctuations (b) downstream of the gate valve at 50% blockage ratio.

Flow pattern data downstream of the local restriction in the form of the gate valve simulator were obtained at the blockage ratios of 25, 50 and 75%. These data included profiles of the average streamwise velocity, $U_x$, and its turbulent fluctuations, $\sigma_U$, downstream of the gate valve. Figures 6–8 show some profiles of $U_x(y)$ and $\sigma_U(y)$ for the case when the gate moved normal to the measurement plane. As the figure shows, good reproducibility of results is observed.

Figure 8. Profiles of velocity (a) and its turbulent fluctuations (b) downstream of the gate valve at 75% blockage ratio.

Conclusions

The results of experimental verification of the approach proposed by the authors to the study of gas flow patterns in circular pipes by the field methods based on the use of the Eiffel chamber analog are presented. On the canonical example of fully developed flow in a circular pipe, the satisfactory performance of the method is shown. The possibility of using the method for estimating the flow parameters in a circular pipe downstream of the gate valve simulator is shown.

References

[1] Faskhutdinov R E, Molochnikov V M, Mikheev N I and Kratirov D V 2009 Trudy Academenergo 1 33–61 (in Russian).
[2] Kratirov D V, Mikheev N I, Molochnikov V M, Faskhutdinov R E and Fañurin V A 2012 Vestnik Kazanskogo Tekhnol. Universiteta 21 140-145 (in Russian).
[3] Sookdeo S, Siddiqui K 2010 Sol. Energy 84 917–927.
[4] Garcia A, Solano J P, Vicente P G and Viedma A 2007 Int. J. Heat Fluid Flow 28 516–525.
[5] Solano J P, Garcia A, Vicente P G and Viedma A 2011 Appl. Therm. Eng. 31 2013–2024.
[6] Hellstrom L H O, Ganapathisubramani B and Smits A J 2015 J. Fluid Mech. 779 701-715.
[7] H. O. Hellstrom, A. Sinha and A. J. Smits 2011 Phys. Fluids 23 011703.
[8] M. Birvalskia, M. J. Tummersa, R. Delfosa and R. A. W. M. Henkes 2014 Int. J. Multiphase Flow 62 161–173.
[9] B. Tadeusz and G. Gørecki 2011 Heat Transfer Engineering 32:2 109-126.
[10] L. Ramai, K. A. Marko and D. Klick 1982 Proc. Combustion Institute 19 259–265.
[11] E. I. Kurkin and V. G. Shakhov 2011 Proc. of the 10th Int. Symp. on Experim. and Comput. Aero-thermodyn. Int. Flows. 4-7 July, Brussels, Belgium. ISAIF10-163, 7.
[12] R. C. Pankhurst and D. W. Holder 1952 Wind-Tunnel Technique London Kent, United Kingdom.
[13] N. I. Mikheev and N. S. Dushin 2016 Instruments and Experimental Techniques 59 882–89.
[14] N. I. Mikheev, A. E. Goltsman, I. I. Saushin and O. A. Dushina 2017 Exp. Fluids 58(8) 97
[15] F. H. Clauser 1954 J. Aeronaut Sci. 21(2) 91–108.
[16] H. Boundary-Layer Theory 1955 New York: McGraw-Hill 535.