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Numerical Investigation of Multiphase Air Flow in a Sudden Expansion Channel Using COMSOL Multiphysics

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Abstract: Sudden expansion channels are widely encountered in engineering systems such as ventilation ducts, heat exchangers, and energy conversion devices, where flow separation and turbulence significantly affect hydraulic losses and system efficiency. This study presents a numerical investigation of multiphase air flow in a sudden expansion channel using the COMSOL Multiphysics computational platform. The governing Navier–Stokes equations coupled with the k–ε turbulence model were employed to simulate turbulent flow regimes in the Reynolds number range of 2000–7000. Velocity fields, pressure distribution, vortex structures, and phase volume fraction contours were analyzed in detail. The numerical results demonstrate the formation of large-scale recirculation zones downstream of the expansion region, accompanied by substantial pressure losses. A comparative analysis with the classical Armaly experimental data confirms the validity of the numerical model. The obtained results provide a reliable theoretical basis for optimizing sudden expansion geometries and reducing energy dissipation in multiphase flow systems.

Keywords: sudden expansion channel, multiphase flow, turbulence modeling, Reynolds number, COMSOL Multiphysics, pressure loss.

1.Introduction. Sudden changes in flow geometry are known to induce complex hydrodynamic phenomena, including flow separation, vortex formation, and enhanced turbulence intensity. In sudden expansion channels, these effects lead to increased energy dissipation and pressure losses, which negatively impact the performance of fluid transport and thermal systems. In multiphase flows, the situation becomes even more complex due to phase–phase interactions, non-uniform phase distribution, and additional momentum exchange mechanisms. Experimental investigations of such flows are often costly and time-consuming, particularly under turbulent conditions. Therefore, computational fluid dynamics (CFD) has become a powerful alternative tool for analyzing multiphase flow behavior in complex geometries.

Previous studies, including the well-known Armaly experiments, have provided valuable insight into flow separation lengths and vortex development in sudden expansion pipes. However, limited attention has been given to multiphase air flow under turbulent conditions using modern numerical platforms. The present work aims to fill this gap by performing a detailed CFD analysis using COMSOL Multiphysics.

2. Mathematical Model and Numerical Method

2.1 Governing Equations

The multiphase turbulent air flow was modeled using the incompressible Navier-Stokes equations, expressing conservation of mass and momentum:

$$\Delta \cdot (p_m u_m) = 0 \qquad (1)$$

2.2 Turbulence Modeling

The k-ε turbulence model was employed due to its robustness and computational efficiency for internal flows. This model solves two additional transport equations for turbulent kinetic energy (k) and its dissipation rate (ε), enabling accurate prediction of recirculation zones and turbulent structures.

Figure 1. Geometry of an abruptly expanding pipe

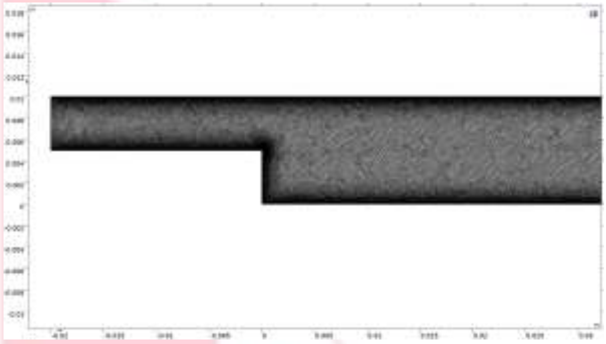

Figure 2. Abruptly expanding pipe network

2.3 Multiphase Flow Modeling

A volume fraction approach was adopted to represent the second phase (solid particles or liquid droplets). The spatial distribution of the phase volume fraction was used to identify phase accumulation regions and interaction zones within the expanded channel.

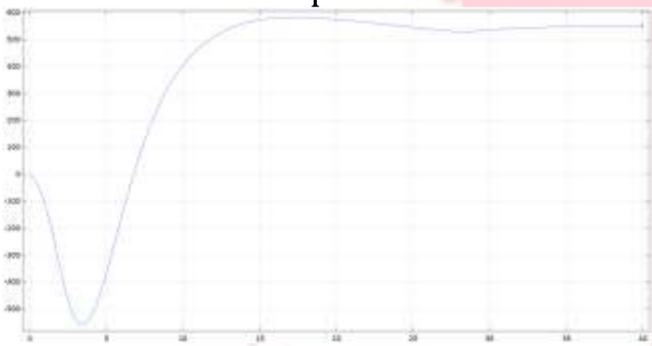

Figure 3. Vortex size at Reynolds number 2000

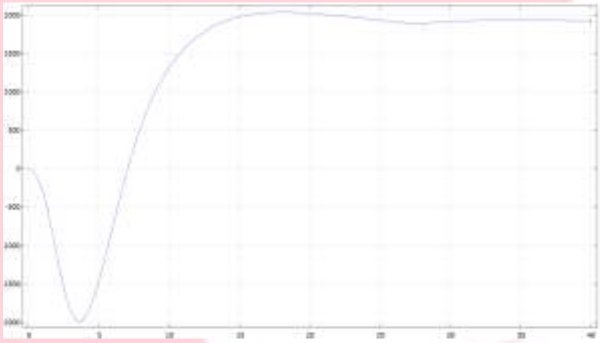

Figure 4. Vortex size at Reynolds number 4000

2.4 Numerical Implementation

The computational domain was discretized using a refined finite element mesh, particularly dense in the sudden expansion region. Boundary conditions included uniform velocity at the inlet and pressure outlet conditions downstream. Simulations were conducted for Reynolds numbers ranging from 2000 to 7000.

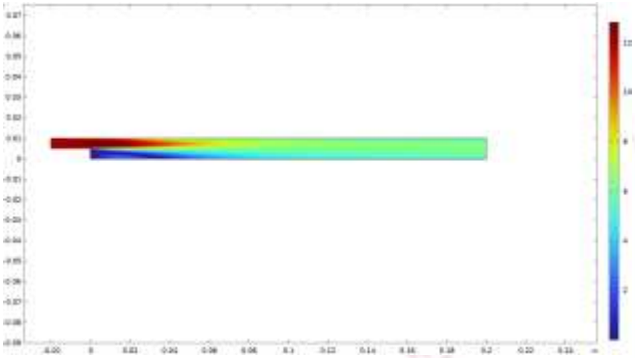

Figure 5. Velocity contour lines

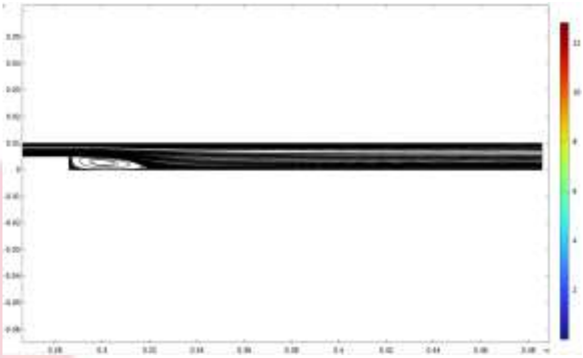

Figure 6. Vortex representation on velocity contour lines

Results. The numerical simulations reveal that immediately after the sudden expansion, the flow separates from the wall, forming a large recirculation zone. Velocity contour plots confirm the presence of reverse flow regions near the channel walls, while high-velocity cores persist in the central region.

Pressure distribution analysis shows a sharp pressure drop at the expansion plane, followed by gradual pressure recovery downstream. As the Reynolds number increases, both the length and intensity of the recirculation zone increase, indicating stronger turbulence effects. Multiphase analysis demonstrates that the secondary phase tends to accumulate within the vortex regions, leading to non-uniform concentration fields and enhanced phase interaction effects.

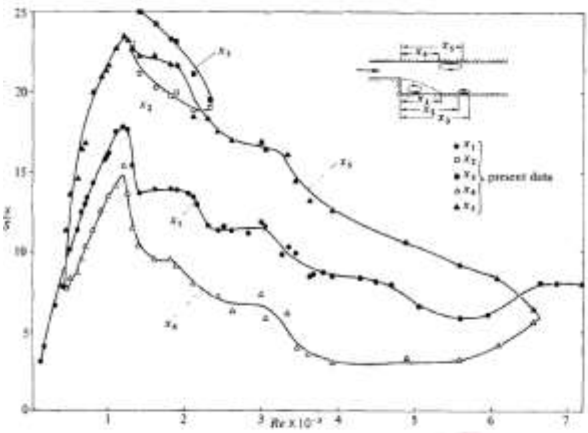

Figure 7. Armaly's experiment

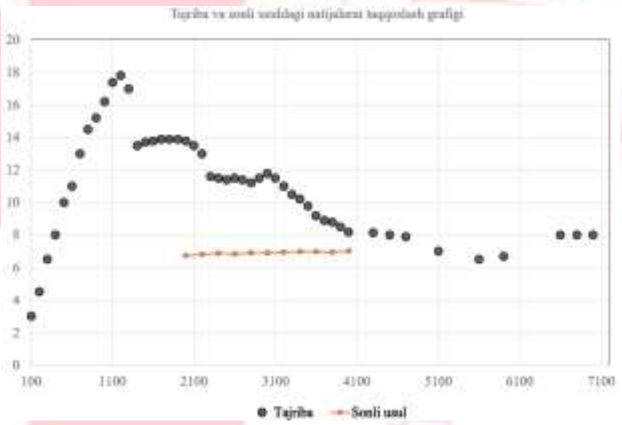

Figure 8. Results from experimental and numerical methods

Discussion. Comparison of the numerically obtained recirculation lengths with the Armaly experimental data shows good agreement, validating the adopted numerical methodology. Minor discrepancies can be attributed to differences in boundary conditions and turbulence modeling assumptions. The results clearly indicate that sudden expansion geometry plays a critical role in determining flow stability and energy losses. In multiphase systems, vortex-induced phase accumulation may significantly influence erosion, noise generation, and thermal performance.

Conclusions. A comprehensive computational fluid dynamics (CFD) investigation of multiphase air flow in a sudden expansion channel was conducted using the COMSOL Multiphysics platform. The adopted numerical framework successfully captured the key hydrodynamic features of turbulent multiphase flow, including flow separation from the channel walls, formation of large-scale recirculation zones, pressure loss mechanisms, and non-uniform phase distribution downstream of the expansion region. The numerical results clearly demonstrate that the sudden expansion geometry significantly alters the flow structure, leading to intense energy dissipation and enhanced turbulence generation. As the Reynolds number increases, both the strength and spatial extent of the recirculation zones increase, resulting in higher pressure losses and stronger vortex dynamics. These findings highlight the dominant role of inertial effects in governing flow behavior under turbulent conditions. Furthermore, the close agreement between the numerical predictions and classical experimental data, such as the Armaly benchmark results, confirms the reliability and accuracy of the proposed numerical approach and turbulence modeling strategy. This validation supports the applicability of the developed model for analyzing complex multiphase flow configurations in engineering systems. Overall, the proposed CFD methodology proves to be an effective and versatile tool for the engineering analysis and optimization of multiphase flow systems involving sudden geometric expansions. The insights gained from this study provide a solid foundation for future research focused on improving channel design, minimizing hydraulic losses, and enhancing the overall efficiency of industrial fluid flow applications.

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