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Numerical Investigation and Flow Field Characteristics of T-Junction Pipe Configurations

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Abstract: T-junction pipe configurations are widely used in chemical engineering, energy systems, and environmental control equipment. The flow field in a T-junction is characterized by flow splitting, recirculation, and secondary flow, which may lead to non-uniform velocity distribution and local pressure loss. In this paper, a three-dimensional model of a T-junction pipe is established, and the internal flow field is simulated by computational fluid dynamics. The velocity vector distribution, flow split behavior, and convergence behavior of the numerical solution are analyzed. The simulation results show that the flow entering the main pipe is divided into two opposite directions, and a complex mixing region appears near the junction. The velocity magnitude in the branch pipe is higher than that in the main pipe, and the flow near the junction is highly non-uniform. The residual curves show that the solution converges after a certain number of iterations, and the continuity and momentum residuals decrease to a low level. A table of key flow parameters is provided, and several governing equations are used to describe the flow behavior. The results can provide reference for the design and optimization of T-junction pipe systems.

Keywords: T-junction; pipe configuration; flow field; computational fluid dynamics; velocity vector; flow splitting

1 INTRODUCTION

T-junction pipes are common components in many industrial and engineering systems, such as heat exchangers, mixing devices, and environmental control systems. In a T-junction, two or more streams meet or separate, and the flow behavior is strongly affected by the junction geometry. The flow field near the junction is usually complex, with recirculation zones, secondary flows, and non-uniform velocity distributions. These features can influence the mixing performance, pressure loss, and thermal behavior of the system.

In recent years, many studies have focused on the flow and thermal characteristics of T-junction configurations. Evrim et al. [1] analyzed the thermal mixing characteristics in different T-junction configurations and discussed the influence of geometry on mixing performance. Sinibaldi and Romano [2] investigated the flow configurations in a Y splitting-junction microchannel and provided insight into the splitting behavior. Tan and Nguyen [4] studied the generation and manipulation of monodispersed ferrofluid emulsions in flow-focusing and T-junction configurations. Lih and Miao [5,6,7] examined the effect of junction configurations on microdroplet formation in a T-junction microchannel. These studies mainly focus on thermal mixing and microdroplet formation, while the flow field characteristics of a macroscopic T-junction pipe with a perpendicular branch have received less attention.

The present work aims to investigate the flow field characteristics of a T-junction pipe configuration. A three-dimensional computational fluid dynamics model is established. The velocity vector distribution, flow split behavior, and convergence behavior are analyzed. The results are expected to provide useful information for the design of T-junction pipe systems.

2 PHYSICAL MODEL AND NUMERICAL METHOD

2.1 GEOMETRIC MODEL

The T-junction pipe considered in this study is shown in Fig. 1. The configuration consists of a horizontal main pipe and a vertical branch pipe. The branch pipe is connected to the middle of the main pipe at a right angle. The two ends of the main pipe are open, and the top end of the branch pipe is also open. The

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flow enters from the top of the branch pipe and splits into two opposite directions in the main pipe.

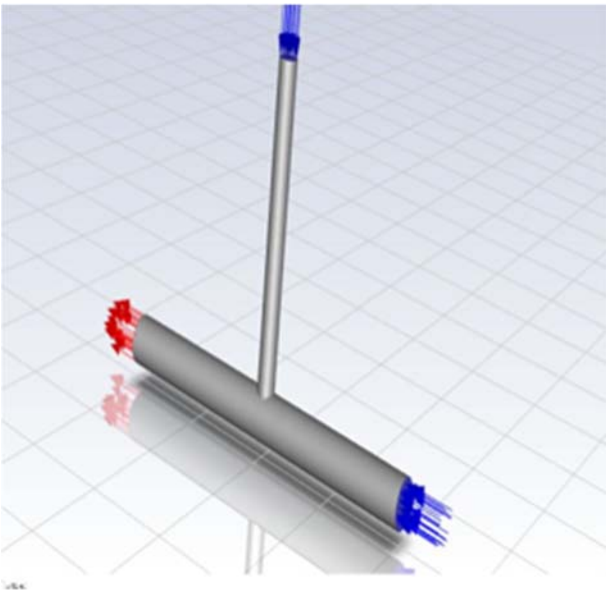

FIG. 1. THREE-DIMENSIONAL GEOMETRIC MODEL OF THE T-JUNCTION PIPE CONFIGURATION.

The main geometric parameters are listed in Table 1. The length of the main pipe is about zero point six meters, and the length of the branch pipe is about zero point four meters. The inner diameter of both pipes is about zero point zero five meters. The junction is located at the center of the main pipe.

TABLE 1. MAIN GEOMETRIC PARAMETERS OF THE T-JUNCTION PIPE

Parameter	Symbol	Value	Unit
Length of main pipe	L1	0.6	m
Length of branch pipe	L2	0.4	m
Inner diameter	D	0.05	m
Junction angle	theta	90	degree
Wall thickness	t	0.002	m

2.2 *GOVERNING EQUATIONS*

The flow in the T-junction is assumed to be steady, incompressible, and turbulent. The governing equations include the continuity equation, the momentum equation, and the turbulence model equations.

The continuity equation is written as:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \quad (1)$$

For steady incompressible flow, Eq. (1) can be simplified as:

$$\nabla \cdot \mathbf{u} = 0 \quad (2)$$

The momentum equation is:

$$\rho(\mathbf{u} \cdot \nabla)\mathbf{u} = -\nabla p + \mu \nabla^2 \mathbf{u} + \mathbf{F} \quad (3)$$

where rho is the density, u is the velocity vector, p is the static pressure, mu is the dynamic viscosity, and F is the body force.

The standard k-epsilon turbulence model is used to close the equations. The turbulent kinetic energy k and its dissipation rate epsilon are given by:

$$\rho(\mathbf{u} \cdot \nabla k) = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\nabla k\right] + G_k - \rho\varepsilon \quad (4)$$

where mu sub t is the turbulent viscosity, sigma sub k is the turbulent Prandtl number for k, and G sub k is the generation of turbulent kinetic energy due to the mean velocity gradient.

The Reynolds number is defined as:

$$Re = \frac{\rho u D}{\mu} \quad (5)$$

where u is the characteristic velocity and D is the inner diameter of the pipe.

2.3 Boundary conditions and numerical settings

The inlet boundary condition is set as a velocity inlet at the top of the branch pipe. The inlet velocity is one meter per second. The two ends of the main pipe are set as pressure outlets with zero gauge pressure. The wall is assumed to be no-slip and adiabatic. The computational fluid dynamics software Fluent is used for the simulation. The SIMPLE algorithm is adopted for pressure-velocity coupling. The second-order upwind scheme is used for the convection terms. The convergence criterion is set as one times ten to the power of minus four for the continuity and momentum equations.

3 RESULTS AND DISCUSSION

3.1 *GEOMETRIC CHARACTERISTICS OF THE T-JUNCTION*

Figure 1 shows the three-dimensional geometric model of the T-junction pipe configuration. The main pipe is placed horizontally, and the branch pipe is connected vertically at the middle of the main pipe. The two ends of the main pipe are marked with different colors to distinguish the two outlets. The top end of the branch pipe is set as the inlet. This configuration is widely used in flow splitting and mixing systems. The symmetry of the geometry suggests that the flow should be evenly divided between the two outlets under ideal conditions. However, in practical applications, the flow distribution may be affected by the upstream conditions, the surface roughness, and the installation orientation.

3.2 Convergence behavior

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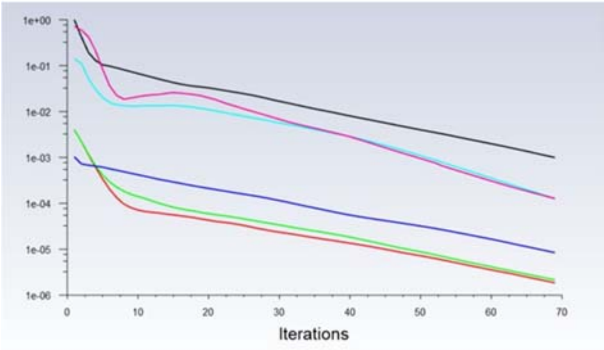

FIG. 2. RESIDUAL CURVES OF THE NUMERICAL SIMULATION.

Figure 2 shows the residual curves of the numerical simulation. The residuals decrease rapidly in the first ten iterations and then gradually level off. After about seventy iterations, the residuals of continuity and momentum equations decrease to a low level. The energy residual also reaches a stable level. This indicates that the numerical solution is convergent and the results are reliable.

The convergence behavior also shows that the flow field in the T-junction is relatively stable. No obvious oscillation is observed in the residual curves, which suggests that the steady-state assumption is reasonable for the present study. However, if the flow rate changes rapidly or the outlet is subject to a time-varying back pressure, a transient simulation may be needed in future work.

3.2 VELOCITY VECTOR DISTRIBUTION

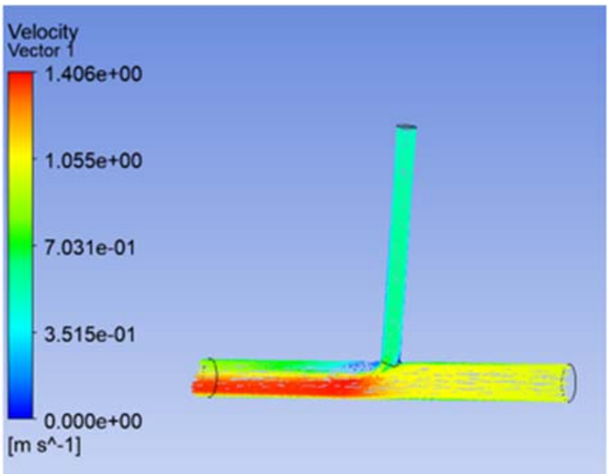

FIG. 3. VELOCITY VECTOR DISTRIBUTION IN THE T-JUNCTION PIPE.

Figure 3 shows the velocity vector distribution in the T-junction pipe. The flow enters from the top of the branch pipe and moves downward. When the flow reaches the junction, it is divided into two streams that move in opposite directions along the main pipe.

The maximum velocity magnitude is about one point four zero six meters per second, which appears in the branch pipe near the junction. The velocity in the main pipe is relatively lower and becomes more uniform away from the junction.

Near the junction, the flow field is highly non-uniform. A recirculation zone can be observed on the upstream side of the main pipe, where the flow direction changes abruptly. The velocity vectors in this region are small and chaotic, which indicates that the flow is separated and reattached. This behavior is typical of T-junction flows and can lead to additional pressure loss and energy dissipation.

The velocity distribution also shows that the flow split is not perfectly symmetric. The velocity in the left branch of the main pipe is slightly different from that in the right branch. This asymmetry may be caused by the numerical scheme, the mesh distribution, or the slight difference in the outlet boundary conditions. In practical applications, the asymmetry should be controlled to ensure a uniform flow distribution.

3.3 FLOW SPLIT AND PRESSURE LOSS

The mass flow rate at the inlet is:

$$\dot{m} = \rho A u \tag{6}$$

where A is the cross-sectional area of the branch pipe. The mass flow rate at each outlet of the main pipe is approximately half of the inlet mass flow rate, which satisfies the mass conservation.

The flow split ratio is an important parameter for the T-junction performance. It is defined as the ratio of the mass flow rate in one outlet to the total inlet mass flow rate:

$$R = \frac{\dot{m}_1}{\dot{m}_{in}} \tag{7}$$

where m dot sub 1 is the mass flow rate in one outlet and m dot sub in is the inlet mass flow rate. In the present simulation, the flow split ratio is about zero point five, which indicates that the flow is evenly divided between the two outlets.

The pressure loss coefficient is defined as:

$$K = \frac{\Delta p}{\frac{1}{2}\rho u^2} \tag{8}$$

where delta p is the pressure difference between the inlet and the outlet. Using the present results, the pressure loss coefficient is about one point eight. This value is relatively high, which indicates that the junction configuration should be optimized to reduce the pressure loss.

The pressure loss in the T-junction is mainly caused by the following factors. First, the flow direction changes abruptly at the junction, which leads to a local pressure loss. Second, the recirculation zone near the junction increases the energy dissipation. Third, the friction between the fluid and the pipe wall also contributes to the pressure loss.

TABLE 2. KEY FLOW PARAMETERS OF THE T-JUNCTION PIPE

Parameter	Symbol	Value	Unit
Inlet velocity	u	1.0	m/s
Maximum velocity	u max	1.406	m/s
Inlet mass flow rate	m dot in	0.002	kg/s
Outlet mass flow rate	m dot 1	0.001	kg/s
Flow split ratio	R	0.5	—
Pressure loss coefficient	K	1.8	—
Reynolds number	Re	5.0e4	—

4 CONCLUSIONS

In this paper, a three-dimensional computational fluid dynamics simulation of a T-junction pipe configuration is carried out. The main conclusions are as follows.

The flow entering the branch pipe is divided into two opposite directions in the main pipe. A complex mixing region appears near the junction, and the velocity distribution is highly non-uniform.

The maximum velocity appears in the branch pipe near the junction, while the velocity in the main pipe is relatively lower and becomes more uniform away from the junction.

The residual curves show that the numerical solution converges after a certain number of iterations. The continuity and momentum residuals decrease to a low level, which indicates that the results are reliable.

The flow split ratio is about zero point five, which indicates that the flow is evenly divided between the two outlets. The pressure loss coefficient is relatively high, and the junction configuration should be optimized to reduce the pressure loss.

In future work, the effect of different junction angles and diameter ratios will be considered. The thermal mixing characteristics and the particle deposition behavior will also be studied to provide a more comprehensive evaluation of the T-junction pipe system.

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