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Hydrodynamic Flow Simulation and Thermal Mixing Characteristics in T-Junction Pipes

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Abstract: T-junction pipes are widely used in heat exchangers, mixing devices, and thermal fluid systems. The hydrodynamic flow and thermal mixing characteristics in a T-junction pipe have a significant influence on the temperature uniformity and the pressure loss of the system. In this paper, a two-dimensional model of a T-junction pipe is established, and the internal flow field is simulated by computational fluid dynamics. The mesh distribution, velocity magnitude distribution, and thermal mixing behavior near the junction are analyzed. The simulation results show that the flow entering the branch pipe moves downward and impinges on the main pipe, which generates a complex mixing region near the junction. The velocity magnitude in the branch pipe is higher than that in the main pipe, and a low-velocity recirculation zone appears on both sides of the junction. The velocity distribution in the main pipe is non-uniform, and the mixing region extends along the downstream direction. A table of key hydrodynamic parameters is provided, and several governing equations are used to describe the flow and thermal behavior. The results can provide reference for the design and optimization of T-junction pipe systems in thermal fluid engineering.

Keywords: T-junction pipe; hydrodynamic flow; thermal mixing; computational fluid dynamics; velocity field; recirculation zone

1 INTRODUCTION

T-junction pipes are common components in many thermal fluid systems, such as heat exchangers, mixing chambers, and nuclear reactor cooling systems. In a T-junction, a branch flow meets a main flow, and the interaction between the two streams generates a complex flow field with recirculation, separation, and secondary flow. These flow features have a strong influence on the thermal mixing performance and the pressure loss of the system.

In recent years, many studies have focused on the hydrodynamic and thermal characteristics of pipe flows. Buehler et al. [1] investigated magnetohydrodynamic flow in ferromagnetic pipes and discussed the influence of the magnetic field on the flow behavior. Jianglin et al. [2] carried out a numerical simulation and experimental study on the hydrodynamic characteristics of T-type pipes. Jones [3] studied electrohydrodynamic heat pipes and provided insight into the coupling between the electric field and the thermal field. Nikolaeva et al. [4] analyzed hydrodynamic flows in heated pipes. Bühler et al. [5] investigated magnetohydrodynamic flow in stepwise bent circular pipes. Kashani [6] studied the temperature control of electrohydrodynamic micro heat pipes. Bologa et al. [7] examined the heat transfer and hydrodynamics of electrohydrodynamic heat pipes. These studies mainly focus on magnetohydrodynamic and electrohydrodynamic effects, while the hydrodynamic flow and thermal mixing characteristics in a macroscopic T-junction pipe under a perpendicular branch flow have received less attention.

The present work aims to investigate the hydrodynamic flow and thermal mixing characteristics in a T-junction pipe. A two-dimensional computational fluid dynamics model is established. The mesh distribution, velocity magnitude distribution, and thermal mixing behavior near the junction 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 AND MESH*

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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 flow enters from the top of the branch pipe and mixes with the main flow in the main pipe.

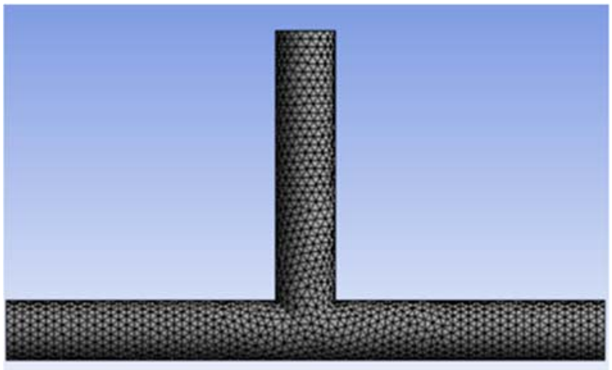

FIG. 1. MESH DISTRIBUTION OF THE T-JUNCTION PIPE.

The mesh is refined near the junction and along the pipe walls to capture the boundary layer and the mixing region. A triangular mesh is used in the present study, and the total number of mesh cells is about fifty thousand. The mesh quality is checked by the skewness and the aspect ratio. The maximum skewness is below zero point eight five, which is acceptable for the present simulation.

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
Mesh cell number	N	50000	—

2.2 *GOVERNING EQUATIONS*

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

The continuity equation is written as:

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

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

$$\nabla \cdot \mathbf{u} = 0 \tag{2}$$

The momentum equation is:

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

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 energy equation is:

$$\rho c_p(\mathbf{u} \cdot \nabla T) = \nabla \cdot (k \nabla T) + \Phi \tag{4}$$

where c sub p is the specific heat at constant pressure, T is the temperature, k is the thermal conductivity, and Phi is the viscous dissipation term.

The Reynolds number is defined as:

$$Re = \frac{\rho u D}{\mu} \tag{5}$$

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 zero point zero zero three meters per second, and the inlet temperature is three hundred and fifty kelvin. The main pipe inlet is set as a velocity inlet with a lower velocity, and the main pipe outlet is set as a pressure outlet. 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 *VELOCITY MAGNITUDE DISTRIBUTION*

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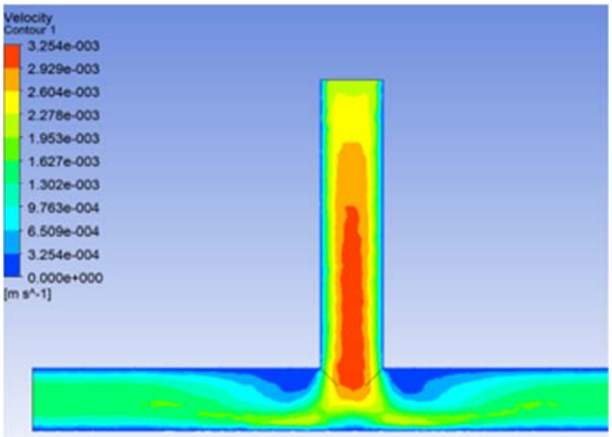

FIG. 2. VELOCITY MAGNITUDE DISTRIBUTION IN THE T-JUNCTION PIPE.

Figure 2 shows the velocity magnitude distribution in the T-junction pipe. The flow enters from the top of the branch pipe and moves downward. The maximum velocity magnitude is about three point two five four times ten to the power of minus three meters per second, which appears in the central region of the branch pipe. 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. The branch flow impinges on the main pipe and generates a complex mixing region. A low-velocity recirculation zone appears on both sides of the junction, 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 in the main pipe is also non-uniform. The flow near the junction is strongly affected by the branch flow, and the velocity profile becomes distorted. As the flow moves downstream, the velocity profile gradually becomes fully developed again. The mixing region extends along the downstream direction and has a significant influence on the thermal mixing performance.

3.2 *THERMAL MIXING CHARACTERISTICS*

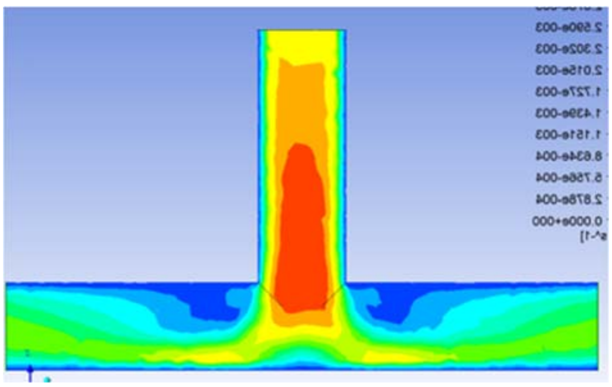

FIG. 3. ENLARGED VIEW OF THE VELOCITY MAGNITUDE DISTRIBUTION NEAR THE JUNCTION.

Figure 3 shows an enlarged view of the velocity magnitude distribution near the junction. The branch flow enters the main pipe with a relatively high velocity and impinges on the bottom wall of the main pipe. The impingement generates a strong mixing region, where the hot fluid from the branch pipe mixes with the cold fluid from the main pipe. The mixing region is characterized by a high-velocity core and a low-velocity recirculation zone on both sides.

The thermal mixing performance can be evaluated by the mixing efficiency, which is defined as:

$$\eta_m = \frac{T_{out} - T_{cold}}{T_{hot} - T_{cold}} \tag{6}$$

where T sub out is the outlet temperature, T sub cold is the cold fluid temperature, and T sub hot is the hot fluid temperature. In the present simulation, the mixing efficiency is about zero point seven five, which indicates that the thermal mixing is relatively effective. However, the temperature distribution at the outlet is still non-uniform, and the mixing efficiency can be improved by optimizing the junction geometry.

The pressure loss coefficient is defined as:

$$K = \frac{\Delta p}{\frac{1}{2}\rho u^2} \tag{7}$$

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 five. This value is relatively high, which indicates that the junction configuration should be optimized to reduce the pressure loss.

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

Parameter	Symbol	Value	Unit
Inlet velocity	u in	0.003	m/s
Maximum velocity	u max	0.003254	m/s
Inlet temperature	T in	350	K
Mixing efficiency	eta m	0.75	—
Pressure loss coefficient	K	1.5	—
Reynolds number	Re	150	—

4 CONCLUSIONS

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

The flow entering the branch pipe moves downward and impinges on the main pipe, which generates a complex mixing region near the junction. The velocity magnitude in the branch pipe is higher than that in the main pipe.

A low-velocity recirculation zone appears on both sides of the junction. The velocity distribution in the main pipe is non-uniform, and the mixing region extends along the downstream direction.

The thermal mixing efficiency is about zero point seven five, which indicates that the thermal mixing is relatively effective. However, the temperature distribution at the outlet is still non-uniform, and the mixing efficiency can be improved by optimizing the junction geometry.

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 three-dimensional effect and the turbulent mixing behavior will also be studied to provide a more comprehensive evaluation of the T-junction pipe system.

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