



Thermal Mixing of Hot and Cold Fluids: A Technical Literature Review

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Abstract

Thermal mixing of hot and cold fluids is an important phenomenon in domestic water systems, process equipment, heat-transfer systems and other engineering applications. The quality of mixing is influenced by inlet temperature difference, flow rate, velocity ratio, Reynolds number, junction geometry, branch angle, inlet flow profile and downstream mixing distance. The present article reviews published research on thermal mixing in T-junctions, mixing tees and mixing valves. Experimental investigations and numerical approaches including computational fluid dynamics, large-eddy simulation and improved delayed detached-eddy simulation have been considered. The reviewed studies report that strong temperature gradients and fluctuations occur near the mixing region, while temperature uniformity generally increases downstream. Flow structures such as shear layers, recirculation zones and vortices play an important role in transporting hot and cold fluid across the mixing interface. The literature also indicates that changes in branch angle, inlet flow profile, flow-rate ratio and internal valve geometry can significantly alter the thermal mixing behavior. Recent studies have extended the investigation from simple T-junctions to practical mixing-valve configurations. The review identifies the major parameters affecting thermal mixing and summarizes the development of research in this field.

Keywords

Thermal mixing; hot and cold fluid; T-junction; mixing valve; computational fluid dynamics.

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1. INTRODUCTION

Thermal mixing occurs when two fluid streams having different temperatures enter a common flow passage. During the mixing process, momentum is exchanged between the streams and heat is transferred from the hot fluid to the cold fluid. Immediately after the two streams meet, the temperature field is generally non-uniform. With increasing downstream distance, convection, turbulent transport and heat conduction reduce the temperature difference and gradually produce a more uniform temperature distribution.

T-junctions are commonly used to investigate thermal mixing because the geometry provides a simple arrangement in which a branch stream enters a main stream. The interaction between the two streams produces shear layers, vortices and recirculation regions. These structures transport fluid between the hot and cold regions and strongly influence the temperature field. Mixing tees work on a similar principle, while mixing valves provide a practical configuration in which hot and cold streams are controlled and combined inside a compact internal passage.

Thermal mixing has been investigated using both experimental and numerical methods. Experimental studies provide temperature and velocity measurements at selected locations, whereas computational fluid dynamics (CFD) provides detailed information about the velocity, pressure, temperature and turbulent flow fields inside the mixing region. High-fidelity methods such as large-eddy simulation (LES) and improved delayed detached-eddy simulation (IDDES) have also been used to investigate unsteady flow structures and temperature fluctuations.



Several researchers have investigated the influence of valve type, junction geometry, branch angle, flow-rate ratio, inlet velocity, inlet flow profile and downstream distance on mixing behaviour [1–8]. The collection of these studies provides useful information about the mechanisms responsible for thermal homogenization and the parameters that influence mixing performance. The major findings reported in the literature are reviewed chronologically in the following sections

2. LITERATURE SURVEY REPORT

One of the earliest reported investigations [1] examined converging T-junctions with large inlet temperature differences, showing that mixing improved with downstream distance and approximately 50% homogenization was achieved around 3D. Other works [2,3] explored the influence of branch angle and flow configuration, highlighting that geometry strongly affects vortex formation and temperature distribution. A preliminary numerical study [4] emphasized that mixing efficiency depends on both flow momentum and thermal gradients.

Later studies [5] expanded to transient vortex structures and inlet flow profiles. It was demonstrated that different inlet velocity profiles produce distinct vortex roll-up patterns, significantly altering local mixing. Single roll-up vortices were associated with weaker entrainment, while double roll-up structures enhanced mixing efficiency. These findings emphasized the importance of specifying realistic inlet conditions in CFD simulations.

More recent investigations [6] compared short and long mixing tees, showing that longer downstream sections provide greater opportunity for hot and cold streams to interact. Higher inlet velocities improved mixing performance, confirming the role of momentum exchange. Work on mixing valves [7] extended the analysis to internal flow structures, demonstrating that valve geometry and component arrangement influence temperature fluctuations and mixing uniformity.

Comparative analyses [8] reinforced that CFD is an effective tool for resolving velocity, temperature, and turbulence structures, but results remain configuration-specific. Differences in turbulence models, mesh resolution, and boundary conditions were shown to affect predicted mixing behaviour.

3. FACTORS AFFECTING THERMAL MIXING

The reviewed studies indicate that thermal mixing is controlled by several interacting parameters. The major factors reported in the literature are summarized below.

The difference between the hot and cold inlet temperatures affects the thermal gradient within the mixing region. A larger temperature difference produces greater temperature variation between the two streams. The study by Nuruzzaman et al. [3] considered a temperature difference of 339 K, while the studies by Lampunio et al. [6] and Singh et al. [8] considered 17°C. The different operating conditions demonstrate that temperature difference must be considered together with flow and geometry.

The relative flow rates of the main and branch streams determine the momentum exchange at the junction. Increasing the branch-to-main flow-rate ratio can increase penetration of the secondary stream into the primary flow. The work reported in [5] associated higher flow-rate and velocity ratios with improved mixing for the investigated configurations.

The geometry of the mixing region directly affects the flow pattern. Branch diameter, main-pipe diameter, branch angle and downstream length influence the location and strength of shear layers and vortices. Nan et al. [4] demonstrated that changing the branch angle from 90° to 45° changed the vortex structures and mixing behaviour.

A sufficient downstream distance is required for the hot and cold streams to interact. The results of [3] showed that mixing increased with downstream distance, with approximately 50% mixing around 3D for the investigated configuration. Singh et al. [8] similarly reported improved mixing with increased tee length.

The inlet velocity profile affects the formation of turbulent structures. Lampunio et al. [6] demonstrated that different inlet profiles produced different vortex structures and consequently different transient thermal mixing behaviour.



In practical mixing valves, internal components can alter the direction and intensity of incoming fluid jets. Yang et al. [7] demonstrated that plunger stroke influenced the jet angle and temperature fluctuations inside the valve.

4. COMPARATIVE ANALYSIS

The major parameters and findings reported in the reviewed literature are presented in Table 1.

TABLE 1. Comparison of reviewed thermal-mixing studies.

Ref.	Configuration	Method	Major parameter	Major finding
[1]	Domestic mixing valve	Experimental + numerical	Valve type, circulation flow	Temperature stability and pressure drop affected system performance
[2]	T-junction	LES + experiment	Flow structure, wall effect	Stratification and vortices affected temperature fluctuations
[3]	90° T-junction	CFD	Flow ratio, ΔT	~50% mixing around 3D for investigated case
[4]	45°/90° T-junction	Experiment + LES	Branch angle	Branch angle changed vortex structure and mixing
[5]	T-junction	CFD	Flow/velocity ratio	Higher ratios associated with improved mixing
[6]	T-junction	IDDES-SST	Inlet profile	Inlet profile changed turbulent structures
[7]	Mixing valve	LES	Plunger stroke	Jet angle and thermal fluctuations changed
[8]	Short/long mixing tee	CFD	Velocity, tee length	Higher velocity and longer mixing distance improved mixing

The comparison shows that the reviewed investigations use different fluids, geometries, dimensions and numerical approaches. Therefore, the numerical values obtained from one study cannot be directly treated as universal values. However, a common trend is observed: sufficient interaction between the hot and cold streams generally improves temperature uniformity, while the flow structures controlling this process depend strongly on geometry and inlet conditions.

Another important observation is the development of numerical methods. Earlier practical investigations considered system-level valve performance, while subsequent studies used LES and IDDES to investigate unsteady vortices and temperature fluctuations. Recent work has also considered internal mixing-valve geometry rather than only idealized T-junctions.

5. RESEARCH FINDINGS FROM LITERATURE

From the reviewed literature, the following findings can be summarized:

- Thermal mixing is governed by the combined effects of fluid momentum and heat transfer.
- Strong temperature gradients generally occur near the mixing location.
- Temperature uniformity increases with sufficient downstream mixing distance.



- Flow-rate ratio and velocity ratio influence the penetration of the branch stream.
- Branch angle changes the flow pattern and vortex formation.
- Inlet velocity profile can significantly affect transient thermal mixing.
- Internal valve components can change jet direction and temperature fluctuations.
- LES and IDDES provide detailed information about unsteady turbulent structures.
- CFD allows temperature and velocity fields to be investigated throughout the mixing region.
- Numerical values reported in individual studies are dependent on the investigated geometry and operating conditions.

6. RESEARCH GAP

The reviewed literature covers a wide range of thermal-mixing configurations, including T-junctions, mixing tees and practical mixing valves. However, the investigated geometries, fluids, flow conditions and evaluation methods vary considerably between studies.

Most T-junction investigations concentrate on flow structures, temperature fluctuations and mixing distance, whereas practical valve studies focus on internal flow behaviour, temperature stability or system performance. The literature therefore provides useful information about individual parameters but does not establish a single universal relationship between valve geometry, inlet conditions and mixing uniformity.

Further investigation of compact mixing configurations using numerical analysis can provide additional understanding of the interaction between inlet flow conditions, internal geometry and downstream temperature uniformity.

7. CONCLUSION

The literature reviewed in this article demonstrates that thermal mixing of hot and cold fluids is strongly influenced by inlet temperature difference, flow rate, velocity, branch angle, inlet flow profile, internal geometry and downstream mixing distance. The studies consistently report strong temperature gradients and turbulent structures near the mixing region, followed by progressive reduction in temperature non-uniformity downstream.

The development of research can be observed from practical investigations of domestic mixing valves to detailed numerical investigations of T-junctions and mixing tees. CFD, LES and IDDES have provided detailed information about temperature distribution, vortices, shear layers and transient fluctuations. The reviewed studies also demonstrate that changes in geometry and inlet conditions can substantially alter the mixing behaviour.

Although common trends are observed, the numerical values reported in the literature are configuration-specific. Therefore, published results must be interpreted according to the fluid, geometry, boundary conditions and computational method used in each investigation. Overall, the literature establishes CFD as an effective approach for understanding thermal mixing and evaluating the influence of flow and geometric parameters.

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