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A novel low-resistance duct tee emulating a river course

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ABSTRACT

Duct fittings are integral parts of a duct system and play important roles in fluid transportation. Resistance within the component directly affects the energy consumed by fans and pumps. This paper proposes a novel low-resistance duct tee by emulating a natural river configuration and theoretically explains the mechanism of resistance reduction in ducts based on variations in dissipation and displacement terms in the N—S equation. The novel tee can reduce resistance in straight ducts with any flow ratios and aspect ratios, with a resistance reduction rate from 20.45% to 248.21%. The novel tee can also reduce resistance in branch ducts only when the flows in straight ducts are larger than in branch ducts, and the resistance reduction rate is between 0 and 817.88% (The resistance reduction rate is the degree of resistance reduction achieved by the novel duct tee). The resistance reduction rate can be improved to above 100% when the increased amplitude of momentum dissipation is below the increased amplitude of momentum convection. The turbulence model was selected based on the full-scale experiment. The resistance reduction effect of the novel tee is validated via a full-scale experiment at the end of this paper.

1. Introduction

Duct fittings, such as elbows and tees, are integral parts of a duct system and play an important role in fluid transportation. Resistance in the duct fittings directly affects energy consumption by fans and pumps. The energy consumption induced by duct fittings accounts for approximately 5%–10% of annual building energy consumption [1–3]. Therefore, the resistance of duct fittings in ducts has drawn increasing attention, and scholars have considered various techniques to reduce resistance in duct systems [4–6].

When considering resistance reduction, a river course provides valuable insights into natural processes. For example, the Yellow River, China's mother river, formed a shape of low resistance over 10 thousand to 100 thousand years of flowing because river paths with high resistance were washed away and reconsolidated. In addition, there are many similarities between a river course and a duct system; the main stream is similar to the most unfavorable loop of the duct system, and the confluence area of the river is similar to the duct tee. These similarities provide a new perspective for reducing resistance in tees and other duct fittings in duct systems. In recent years, many studies have adopted bionics or emulation to optimize equipment performance. Kim (2018) introduced the forced convection heat transfer from the biomimetic cylinder inspired by a harbor seal vibrissa [7]. Wang (2016) designed a new type of Darrieus vertical-axis wind turbine with blades that could automatically transform into the desired geometrical shapes to improve aerodynamic performance, making the turbine less hazardous to birds and bats while maintaining a lower cost [8]. Yuan (2015) presented a new artificial bee colony algorithm search strategy based on quantum theory and chaotic local optimizers (QCABC), which was employed to solve the optimal power flow (OPF) issue [9]. Zeiny (2012) applied bionics principles to study shell-shaped buildings using sunlight to save indoor power consumption on illumination [10]. The above concepts were successfully implemented in their corresponding investigations and thus provide an important basis for the present study to optimize duct fittings of duct systems according to the characteristic shapes of a river course.

Donald. S. Miller (1978) researched the tee shape, convergence, branching, velocity ratio, Reynolds number (Re) and main-branch-duct angle effects on the local resistance coefficient [11]. Gan (2000) studied the local resistance coefficients of branching and converging tees; the results indicated that the local resistance coefficients at a joint are related to the branch flow proportion in the total flow of the main duct, thus providing the curves for the local resistance coefficients [12]. Rahmeyer (2002) studied diverging tees of certain shapes and found that the local resistance coefficient of the branch duct is related only to the velocity ratio between the branch duct and the main duct and is

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uncoupled with the area ratio of the branch to the main duct, section geometry of the main duct, Reynolds number Re and interaction among adjacent tees [13]. S. Q. Li (2015) studied the local resistance of steam condensate flowing in a tee by adopting CFD simulation and obtained a quantitative conclusion on the effects of the steam bubble size and moderate temperatures on the local resistance [14]. These representative studies are mostly based on the resistance characteristics of tees to obtain the resistance coefficient. However, further research is needed to reduce the resistance by optimizing the shape based on these resistance characteristics.

Theoretical knowledge on duct or pipe resistance has always been confined to the Darcy-Weisbach formula [15–18]; the formula for local resistance of a duct is $h_f = \lambda \frac{L}{D}\frac{V^2}{2g}$. However, the Darcy formula is a phenomenological formula with three disadvantages:

- The local resistance coefficient is a single value and cannot be used to evaluate the resistance field. Furthermore, the local resistance coefficient cannot be used to characterize the high-resistance area in the field to provide instructions for optimizing the shapes of duct fittings.
- The local resistance coefficient can only reflect the energy loss terms of the energy equation, and the energy conversion process is not incorporated.
- The most important local resistance coefficient in the formula is obtained via experiments, but no theory exists to describe the elimination of resistance.

Therefore, the Darcy-Weisbach formula cannot be used to reduce resistance in duct fittings of a duct system. Is there any other theoretical approach available for this purpose? This paper attempts to answer this question from the perspective of energy dissipation.

Our research group has published numerous papers on duct resistance reduction. The former works were primarily concerned with using a guide vane and bionics approach to reduce resistance [19–20]. We also proposed adopting the energy dissipation rate to describe the resistance field [21]. However, all of the above studies were focused on the split duct tee, while this study focused on the confluence duct tee.

This paper focuses on a novel concave tee with low resistance based on the emulation of a river configuration and theoretically explains the mechanism of reducing resistance in ducts based on variations in the dissipation and displacement terms in the N—S equation. The effect of a concave shape on resistance reduction under different aspect ratios and flow ratios is introduced, and an analysis of the normalized height, dissipation, convection, and pressure gradient is conducted. The research results are verified by a full-scale experiment described at the end of this paper. The novel concave tee creates a negative resistance force under some conditions, thus providing a new method for reducing resistance in tees and other duct fittings in duct systems.

2. Analysis of the resistance reduction mechanism

2.1. Concepts of resistance reduction

Fig. 1 shows China's mother river, the Yellow River, which is the fifth-largest river in the world. There is always a concave embankment formed at the confluence area. There are two possible reasons for this concave shape [22,23]:

- The formation of a river embankment is a dynamic balance process of sediment deposition. In this process, the sediment hindering the flow will be washed away by the confluence. The final shape in the confluence area has the lowest resistance.
- In the confluence area, the drop in the tributaries is the main force in the section of the river course. Thus, the shape of the river always develops toward the direction of the lowest flow resistance of tributaries. If it does not, after 100,000 years of river scouring, this section of the tributary will be diverted or disconnected.

Thus, to reduce resistance in ducts, is it possible to add this concave shape into a tee similar to the river course? In addition, compared with rivers, duct systems have the following advantages: 1. a converging tee has a relatively fixed shape. 2. The flow in the air duct is a constant value accurately calculated in the design process, which means that the duct constitutes a fully characterized system with ducts holding a well-controlled air flow. Without the uncertainties in rivers, it is easier to achieve low resistance in the air duct.

2.2. Analysis of the mechanism of resistance reduction

This condition can be further explained by an N—S equation from the microscopic perspective (incompressible viscous fluid, steady flow and adiabatic flow) [24]:

$$\frac{\partial \vec{v}}{\partial t} + (\vec{v}\cdot\nabla)\vec{v} = \vec{f} - \frac{1}{\rho}\nabla p + \upsilon\nabla^2\vec{v} \tag{1}$$

where $\frac{\partial \vec{v}}{\partial t}$ represents the unsteady term of the fluid, which is 0 in this research; $(\vec{v}\cdot\nabla)\vec{v}$ is the convective term in the fluid, which is an energy conversion process caused by fluid motion; $\vec{f}$ represents volume force inside the fluid per unit, which is 0 in this research; $\frac{1}{\rho}\nabla p$ is the pressure difference of the fluid mass per unit; and $\upsilon\nabla^2\vec{v}$ is the dissipation term in the duct, i.e., the production term for energy dissipation. Thus, the N—S equation can be simplified as

$$\frac{1}{\rho}\nabla p = \upsilon\nabla^2\vec{v} - (\vec{v}\cdot\nabla)\vec{v} \tag{2}$$

This equation shows that $\frac{1}{\rho}\nabla p$ (expanded as $\frac{1}{\rho}\frac{\partial p}{\partial x}$, $\frac{1}{\rho}\frac{\partial p}{\partial y}$, and $\frac{1}{\rho}\frac{\partial p}{\partial z}$) actually represents pressure changes over different directions and can represent pressure reduction in the duct, that is, resistance.

$\upsilon\nabla^2\vec{v}$ is the viscosity dissipation term characterizing momentum dissipation caused by viscosity [25,26]. As shown, this equation is composed of velocity gradients in the different directions $\frac{\partial u_x}{\partial y}$ and $\frac{\partial u_y}{\partial x}$. Take the tee in Fig. 2 as an example: to reduce resistances in the tee, the velocity gradient $\frac{\partial u_x}{\partial y}$, $\frac{\partial u_y}{\partial x}$ should be minimized.

The concave shape in the tee reduces the cross-sectional area of the tee,

- increases u_x and u_y and thus increases the velocity gradients $\frac{\partial u_x}{\partial y}$ and $\frac{\partial u_y}{\partial x}$, and increases the value of the differential dissipation term. If the integral area is unchanged, the integral term of the dissipative item will increase.
- Furthermore, this shape reduces the integral domain at the tee and decreases the integral value of the dissipation term. If the differential value is unchanged, the integral term of the dissipative term will decrease.

  The final integral value of the dissipation term may increase or decrease according to the competing mechanisms.

Similarly, $(\vec{v}\cdot\nabla)\vec{v}$ is the displacement term of momentum [27,28], which can be expanded as follows, taking the x-direction as an example: $u_x\frac{\partial u_x}{\partial x} + u_y\frac{\partial u_x}{\partial y}$. Both u_x and u_y at the red-circled confluence area of the tee in Fig. 2 are almost positive values. For calculating the resistance at the direction of the straight duct, the concave part leads to a smaller cross-section area of the confluence area of the tee, increasing u_x and u_y. Thus, $u_x\frac{\partial u_x}{\partial x} + u_y\frac{\partial u_x}{\partial y}$, i.e., $(\vec{v}\cdot\nabla)\vec{v}$ increases; however, the integral domain decreases.

Equation (2) indicates that when the duct is concave, $\frac{1}{\rho}\nabla p$ may decrease, which depends on the following two conditions: