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Compressible fluid flow field synergy principle and its application to drag reduction in variable-cross-section pipeline

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ABSTRACT

The compressible fluid flow field synergy principle was presented as an effective theoretical guide to reduce the drag during compressible flow. A compressible flow field synergy model was presented based on the incompressible flow field synergy principle. A variable cross-section pipeline air of compressible flow was used to verify the model. Two specific improvement schemes were studied for practical applications, which showed a 24% and 20% reduction in the resistance.

1. Introduction

The past few decades have witnessed a growing interest in the field synergy principle. These studies have primarily focused on two aspects: heat convection and drag reduction in flow. To boost the heat transfer performance, Guo et al. [1–4] introduced the concept of field synergy and consequently garnered significant attention from other researchers. This concept focuses on the strength of the heat convection, which not only depends on the temperature gradient field, the velocity field in the fluid domain and the fluid property, but also on the included angle size between the velocity field and heat flow field. The size of the included angle negatively correlates with the degree of field synergy and the heat transfer efficiency. Field synergy theory was first applied to a laminar convection heat exchange process [1]. Subsequently, it has been numerically and experimentally validated in laminar and turbulent flow and applied to the analysis of heat exchangers [2–4].

The reduction of flow drag is a fundamental problem in hydrodynamics. So far, researchers have devised a variety of technologies to reduce flow drag. For example, objects in the external flow are designed to streamline or improve the surface roughness to delay the boundary layer separation; for internal flow, guide plates are placed in the bend to avoid secondary separation. However, most of the presented flow drag reduction technology is based on experience and lacks a unified theory. Chen et al. [5] began with the incompressible fluid flow drag reduction problem and explored the feasibility of solving this problem by using the field synergy theory. As a result, they presented a field synergy drag reduction model. They also deduced the incompressible flow field synergy equation according to the principle of the minimum dissipation of mechanical energy. By solving the equation, the optimal incompressible flow can be obtained to effectively guide the optimisation of pipeline design.

Many researchers [6–14] have focused on studying the heat transfer field synergy presented by Guo. To quantitatively describe and compare the degree of field synergy between the velocity vector and temperature gradient vector, previous researchers have analysed and discussed the evaluation index in the heat transfer field synergy. The published literature indicates that the evaluation index of the field synergy mainly includes three aspects: (1) the included angle between the velocity vector and the temperature gradient vector; (2) the cosine of the included angle between the velocity vector and the temperature gradient vector; and (3) the field synergy number. The included angle between the velocity vector and the temperature gradient vector ranges from 0° to 90° in the heat transfer field synergy [6–10]. When the included angle ranges from 90° to 180°, the supplementary angle is examined. Zhou et al. [12] analysed and discussed the evaluation index of the heat transfer field synergy and presented five methods to calculate the included angle between the velocity vector and temperature gradient vector. They ultimately compared the five

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Nomenclature

B	Lagrange multiplier
D	characteristic length, V/S, m
DC	pressure drop, defined by Eq. (7), dimensionless
F	additional volume force, N
FS	field synergy number, defined by Eq. (8), dimensionless
f	volume force, N
L	length, m
$\vec{n}$	surface unit normal vector
P	pressure, Pa
Re	Reynolds number, dimensionless
S	area of the solid surface, m^2
$\bar{S}$	dimensionless area
S_{ij}	deformation rate tensor
S_{kk}	divergence, dimensionless
t	time, s
$\bar{U}$	dimensionless velocity
u	velocity, m/s
$\bar{u}$	dimensionless velocity
V	volume, m^3
$\bar{V}$	dimensionless volume
x, y, z	Cartesian coordinates, m
Greeks	
β	field synergy angle, degree
δ_{ij}	second order unit tensor, dimensionless
λ	constant
μ	dynamic viscosity, kg/(m s)
v	kinematic viscosity, m^2/s
Π	Lagrange function, W
ρ	density, kg/m^3
φ	viscous dissipation function, W
Subscripts	
i, j	i direction, j direction
x, y, z	Cartesian coordinates
in	inlet
m	mean
ζ	boundary
Ω	domain

calculation methods via numerical simulations. Guo proposed the field synergy number to evaluate the strength of the heat transfer field synergy. Compared with the included angle and its cosine value between velocity vector and temperature gradient vector, the field synergy number better reflects the quality of the heat transfer field synergy. However, the evaluation method has never been mentioned for compressible flow field synergy.

The number of studies undertaken on heat transfer enhancement has been constantly growing since the early 1960s. In 1999, Bergles et al. mentioned nearly 4345 publications on the topic in their literature review [15]. The intensification techniques are numerous [16] and can be classified into two categories: passive and active [17]. Passive techniques enhance heat transfer by modifying the surface exchange or fluid properties, changing the surface geometry, disrupting boundary layers, or promoting liquid–vapour phase changes. Active techniques use jet, spray and electronic methods, etc. to enhance heat transfer. The relevant applications also have a promising future. The aforementioned methods all enhance the heat transfer, but their mechanisms are poorly understood. Therefore, Guo [18] provided a new concept to understand this process. This paper uses this new concept to elucidate further studies.

Drag reduction in gas–liquid two-phase flow is caused by mechanical friction, which is inevitable. Drag can be reduced in pipe flow via two ways. One method consists of adding polymer to the flow [19], the other changes the boundary condition between the flow and solid or the structure of the entire flow field. This study attempts to use the second method to optimise the flow field and obtain new results. The flow drag reduction problem in compressible flow is also very important to design applications, such as the high-speed flow drag reduction problem in pneumatic conveying and aviation devices, etc. The relationship between the flow resistance and the field synergy degree in compressible flow is discussed in this paper. The evaluation method in the heat transfer field synergy is referenced to evaluate the compressible flow field synergy. According to the principle of the minimum dissipation of mechanical energy, a compressible flow field synergy equation was established that takes the equation of continuity as a constraint. Furthermore, a variable cross section of compressible pipe flow was examined as an example to verify the effectiveness of the compressible flow field synergy.

2. Compressible flow field synergy equation

The following model was derived by taking the incompressible field synergy drag reduction model as reference and basing the model on the compressible Navier–Stokes equation.

For compressible flow, the Navier–Stokes equation can be written as follows:

$$\frac{\partial u_\mathrm{i}}{\partial t}+u_\mathrm{j}\frac{\partial u_\mathrm{i}}{\partial x_\mathrm{j}}=f_\mathrm{i}-\frac{1}{\rho}\frac{\partial}{\partial x_\mathrm{j}}\left[\left(P+\frac{2}{3}\mu S_\mathrm{kk}\right)\delta_\mathrm{ij}-2\mu S_\mathrm{ij}\right] \tag{1}$$

The Navier–Stokes equation for steady-state compressible fluid flow without volume force can be written as follows:

$$\int_\Omega \rho u_\mathrm{j}\frac{\partial u_\mathrm{i}}{\partial}x_\mathrm{j}\mathrm{d}V=-\int_\Omega\frac{\partial P}{\partial x_\mathrm{i}}\mathrm{d}V-\int_\Omega\frac{\partial}{\partial x_\mathrm{j}}\left(\frac{2}{3}\mu S_\mathrm{kk}\delta_\mathrm{ij}-2\mu S_\mathrm{ij}\right)\mathrm{d}V \tag{2}$$

Defining $D=V/S$ as characteristic length and introducing the following dimensionless variables:

$$\bar{u}_\mathrm{i}=\frac{u_\mathrm{i}}{u_\mathrm{in}},\quad \bar{u}_\mathrm{j}=\frac{u_\mathrm{j}}{u_\mathrm{in}},\quad \nabla\bar{u}_\mathrm{i}=\frac{\nabla u_\mathrm{i}}{u_\mathrm{in}/D},\quad \mathrm{d}\bar{V}=\frac{\mathrm{d}V}{V},\quad \mathrm{d}\bar{S}=\frac{\mathrm{d}S}{S} \tag{3}$$

yields the following form of Eq. (2):

$$-\frac{D}{\rho}u_\mathrm{in}^2\int_\Omega\frac{\partial P}{\partial}x_\mathrm{i}\mathrm{d}\bar{V}=\frac{\mu}{\rho u_\mathrm{in}^2}\int_\varsigma\left(\frac{2}{3}S_\mathrm{kk}\delta_\mathrm{ij}-2S_\mathrm{ij}\right)\cdot\vec{n}\mathrm{d}\bar{S}+\int_\Omega D\bar{u}_\mathrm{j}\frac{\partial\bar{u}_\mathrm{i}}{\partial x_\mathrm{j}}\mathrm{d}\bar{V} \tag{4}$$

The following has been well established: $\frac{\partial\bar{u}_\mathrm{i}}{\partial x_\mathrm{j}}=\frac{\partial u_\mathrm{i}}{u_\mathrm{in}}\partial x_\mathrm{j}=\frac{\nabla u_\mathrm{i}}{u_\mathrm{in}}$. Thus,

$$\frac{\partial\bar{u}_\mathrm{i}}{\partial x_\mathrm{j}}=\frac{\partial u_\mathrm{i}}{u_\mathrm{in}}\partial x_\mathrm{j}=\frac{\nabla u_\mathrm{i}}{u_\mathrm{in}}=\frac{\nabla\bar{u}_\mathrm{i}}{D} \tag{5}$$

When combined with Eqs. (5) and (4) can be transformed into the following:

$$-\frac{D}{\rho u_\mathrm{in}^2}\int_\Omega\frac{\partial P}{\partial x_\mathrm{i}}\mathrm{d}\bar{V}=\frac{\mu}{\rho u_\mathrm{in}^2}\int_\varsigma\left(\frac{2}{3}S_\mathrm{kk}\delta_\mathrm{ij}-2S_\mathrm{ij}\right)\cdot\vec{n}\mathrm{d}\bar{S}+\int_\Omega\bar{U}\cdot\nabla\bar{u}_\mathrm{i}\mathrm{d}\bar{V} \tag{6}$$

The term on the left side of Eq. (6) is the dimensionless pressure drop in the x_i direction: