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Implementation of the IDEAL algorithm for complex steady-state incompressible fluid flow problems in OpenFOAM

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ABSTRACT

The IDEAL algorithm is an efficient and robust pressure-velocity coupling algorithm, which has been applied in a variety of fluid flow and heat transfer problems. However, the further development of the IDEAL algorithm encounters with two key issues: it is hard to be mastered by other researchers and difficult to be extended to complex engineering problems. In order to overcome these two issues, the IDEAL algorithm is implemented in the world's most widely used open source CFD software - OpenFOAM. In that way, it is convenient for any researcher to employ the IDEAL algorithm to solve complex fluid flow problems. Then, the performance of IDEAL algorithm is analyzed with focus on complex steady-state incompressible fluid flow problems. The results indicate that the IDEAL algorithm is superior to the SIMPLE and SIMPLEC algorithms in convergence and robustness for complex cases. In particular, the IDEAL algorithm can reach convergence, whereas the SIMPLE and SIMPLEC algorithms cannot obtain convergent solution in some cases. This research lays a foundation for a wider application of the IDEAL algorithm in complex engineering problems.

1. Introduction

The SIMPLE [1] (Semi Implicit Method for Pressure Linked Equations) algorithm is a pressure correction algorithm proposed by Patankar and Spalding in 1972. It is the main method for the numerical calculation of incompressible fluid flow and heat transfer problems. The SIMPLE algorithm introduces two basic assumptions. One is that initial velocity and pressure fields are assumed independently, which means that SIMPLE does not reflect the internal relation between the initial pressure and velocity. The other is that the influence of the neighboring-grid velocity corrections is ignored in the process of solving the pressure correction. These two assumptions do not affect the calculation results, but significantly affect the convergence rate of numerical calculation. In order to reduce the defects caused by these two assumptions, more than 10 variants of SIMPLE, such as SIMPLER [2], SIMPLEC [3] and PISO [4], are available in the literature. However, there is no algorithm that has completely overcome the two assumptions.

In 2008, Sun et al. [5,6] proposed the IDEAL algorithm (Inner Doubly-iterative Efficient Algorithm for Linked-equations) on the basis of the CLEAR algorithm [7,8]. In the IDEAL algorithm, two inner iterative calculations for the pressure equation are performed at each iteration level. The first inner iteration for the pressure equation is used to overcome the first assumption of the SIMPLE algorithm. The second inner iteration for the pressure equation is used to overcome the second assumption of the SIMPLE algorithm. Thus, coupling between the velocity and pressure could be fully satisfied, which greatly improves the convergence and stability of calculation process.

At present, the IDEAL algorithm has been successfully extended to structured and unstructured grids. Sun et al. implemented this algorithm on rectangular coordinate staggered grid [9], rectangular coordinate collocated grid [10], and body-fitted grid [11]. The performance of the IDEAL algorithm on these three structured grid systems is systematically compared with many other widely used algorithms, which proved the superiority of the IDEAL algorithm in convergence and robustness. Ding and Sun [12] extended the IDEAL algorithm to two-dimensional unstructured triangular grids. The results show that the IDEAL algorithm based on unstructured grids can also obtain convergent solution in a very wide range of under-relaxation factor and its computational efficiency is more than twice that of the SIMPLE algorithm.

With advantages of fast convergence rate and strong robustness, the

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IDEAL algorithm is employed to solve incompressible and weak compressible flows by many researchers. Tang et al. [13] and Shi et al. [14] employed this algorithm to study the thermal optimization of the roofs constructed with hollow concrete floor system. Lauriat's research group extended the IDEAL algorithm to weak compressible flow [15]. Then, they employed the IDEAL algorithm to simulate the natural convection of the ideal gas non-dilution binary mixture in square cavity [15], the hydrothermal convection in square cavity [16], and the wall condensation or evaporation in humid air-filled cavity [17]. Further, some researchers employed this algorithm to solve two-phase flow and phase change problems. Zhou et al. [18] simulated the gas-liquid two-phase flow problems using the IDEAL algorithm based on unstructured triangular grids. Qu et al. [19] developed a two-dimensional transient model for a passive thermal management system of commercial square lithium ion battery by using the phase change material (PCM) saturated in metallic copper foam. In his model, the IDEAL algorithm is employed to couple the velocity and pressure. Besides, the IDEAL algorithm has also been applied to non-Newtonian fluid [20], multi-component [21], and multi-scale [22–27] flows.

Based on the above analyses, the IDEAL algorithm has been extended to structured and unstructured grids, and has been applied to incompressible and weak compressible, single-phase and two-phase, Newtonian and non-Newtonian fluid, single-component and multi-component, single-scale and multi-scale flow and heat transfer problems. However, the further development of the IDEAL algorithm encounters with two key issues. The first is that existing researches are mainly based on in-house codes, which are hard to be mastered by other researchers. The second is that the IDEAL algorithm is difficult to be extended to complex engineering problems. In order to overcome these two issues, the IDEAL algorithm is implemented in the world's most widely used open source CFD software - OpenFOAM (Open Source Field Operation and Manipulation). OpenFOAM supports arbitrary polyhedral unstructured grids and massively parallel computing. It can deal with large-scale complex fluid flow and heat transfer problems. Furthermore, the software provides a ready-made framework for scientific research and engineering application [28-33]. Therefore, based on OpenFOAM, it is convenient for any researcher to employ the IDEAL algorithm to solve the complex fluid flow problems. Many practical engineering problems, such as turbine sitting, separation equipment, heat exchanger, involve the steady-state incompressible flow and heat transfer phenomena. The numerical calculations for these complex problems sometimes have slow convergence rate and worse robustness, and even cannot obtain convergent solution in some cases. Therefore, in this paper, the IDEAL algorithm is implemented in OpenFOAM to solve the complex steady-state incompressible fluid flow problems, and demonstrates the superiority of its solving performance.

The organizational structure of this article is as follows. The governing equations and discretization process are first introduced in Section 2. Then, the calculation procedure and core code of the IDEAL algorithm are presented in Section 3. Subsequently, the numerical comparison conditions are given in Section 4. In Section 5, two test cases are performed to compare the IDEAL algorithm with the SIMPLE and SIMPLEC algorithms. Finally, the main conclusions are drawn.

2. Governing equations and discretization process

This section describes the governing equations for steady-state incompressible turbulent flow and the corresponding discretization process on arbitrary polyhedral grids.

2.1. Governing equations

Continuity equation:

$$\nabla\cdot\mathbf{U} = 0 \tag{1}$$

where $\mathbf{U}$ is velocity vector.

Table 1
Coefficients in standard k-ε model.

C_μ	σ_k	σ_ε	C_1	C_2
0.09	1.0	1.3	1.44	1.92

Momentum equation:

$$\nabla\cdot(\mathbf{UU}) - \nabla\cdot[(\nu+\nu_t)(\nabla\mathbf{U}+\nabla\mathbf{U}^{\mathrm{T}})] = -\nabla p + \mathbf{g} \tag{2}$$

where ν and ν_t denote the kinematic and turbulent viscosities, respectively. p refers to the kinematic pressure. $\mathbf{g}$ is the gravitational acceleration.

In practical engineering, the standard k-ε model, k-ω model, and k-ω SST model are widely employed to model the turbulent flow.

The governing equations for the standard k-ε model [34]:

$$\nabla\cdot(\mathbf{U}k) - \nabla\cdot\left(\nu + \frac{\nu_t}{\sigma_k}\right)\nabla k = G - \varepsilon \tag{3}$$

$$\nabla\cdot(\mathbf{U}\varepsilon) - \nabla\cdot\left(\nu + \frac{\nu_t}{\sigma_\varepsilon}\right)\nabla \varepsilon = C_1 G\frac{\varepsilon}{k} - C_2\frac{\varepsilon^2}{k} \tag{4}$$

where k is turbulent kinetic energy, ε is turbulent dissipation rate, $\nu_t = C_\mu\frac{k^2}{\varepsilon}$ and $G = 2\nu_t|S_{ij}|^2$. The corresponding coefficients in Eqs. (3) and (4) are shown in Table 1.

The governing equations for the k-ω model [34]:

$$\nabla\cdot(\mathbf{U}k) - \nabla\cdot(\nu + \alpha_k\nu_t)\nabla k = G - C_\mu\omega k \tag{5}$$

$$\nabla\cdot(\mathbf{U}\omega) - \nabla\cdot(\nu + \alpha_\omega\nu_t)\nabla \omega = \gamma G\frac{\omega}{k} - \beta\omega^2 \tag{6}$$

where ω is turbulent specific dissipation rate, $\nu_t = \frac{k}{\omega}$. The corresponding coefficients in Eqs. (5) and (6) are shown in Table 2.

The governing equations for the k-ω SST model [34]:

$$\nabla\cdot(\mathbf{U}k) - \nabla\cdot(\nu + \alpha_k\nu_t)\nabla k = \min(G, c_1\beta^* k\omega) - \beta^* k\omega \tag{7}$$

$$\nabla\cdot(\mathbf{U}\omega) - \nabla\cdot(\nu + \alpha_\omega\nu_t)\nabla \omega = \gamma S - \beta\omega^2 - (F_1 - 1)CD_{k\omega} \tag{8}$$

where

$$\begin{gathered}
\nu_t = \frac{a_1 k}{\max(a_1\omega, b_1 F_2\sqrt{S_2})},\quad \alpha_k = F_1(\alpha_{k1} - \alpha_{k2}) + \alpha_{k2} \\
\alpha_\omega = F_1(\alpha_{\omega1} - \alpha_{\omega2}) + \alpha_{\omega2},\ \beta = F_1(\beta_1 - \beta_2) + \beta_2 \\
\gamma = F_1(\gamma_1 - \gamma_2) + \gamma_2,\quad CD_{k\omega} = 2\alpha_{\omega2}\frac{\nabla k\cdot\nabla\omega}{\omega} \\
F_1 = \tanh\left[\min\left(\min\left(\max\left(\frac{\sqrt{k}}{\beta^*\omega y}, \frac{500\nu}{y^2\omega}\right), \left(\frac{4\alpha_{\omega2}k}{\max(CD_{k\omega}, 1e^{-10})y^2}\right)\right), 10\right)\right]^4 \\
F_2 = \tanh\left[\left[\min\left(\max\left(\frac{2\sqrt{k}}{\beta^*\omega y}, \frac{500\nu}{y^2\omega}\right), 100\right)\right]^2\right]
\end{gathered} \tag{9}$$

The corresponding coefficients in Eqs. (7)–(9) are shown in Table 3.

2.2. Discretization of governing equations

The above mentioned governing equations (Eqs. (2)–(8)) can be written in the following general form:

Table 2
Coefficients in k-ω model.

α_k	C_μ	α_ω	γ	β
0.5	0.09	0.5	0.52	0.072