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基于张量操作和梯度下降的 **SIMPLE** 算法计算效率优化

摘要

本研究针对传统 SIMPLE 算法压力修正过程计算效率低、稳定性受限的瓶颈问题，通过算法架构重构与数值方法创新，提出系统性优化方案。首先，采用张量操作替代传统的循环嵌套编程结构。在 51x51 网格和 0.3 压力松弛因子的测试算例中，计算时间从 265.5 秒显著降低至 80 秒，速度提升约 231%。其次，构建基于自动微分和动态松弛因子的智能梯度解析体系，实现不同网格位置的压力松弛因子自适应调整，减少迭代次数以实现加速计算。此外，考虑到直接求解压力修正值的效率瓶颈，采用梯度下降的优化方法替代传统的求解方式，进一步减少计算时间并提高求解精度。经标准算例验证，优化后的算法在维持高精度前提下，显著增强了复杂流动模拟的实时性与鲁棒性，为工程流体仿真提供了高效可靠的新范式。

关键词

SIMPLE 算法；张量操作；自适应压力松弛；梯度下降

Abstract

This study addresses the computational inefficiency and stability limitations of the traditional SIMPLE algorithm's pressure correction process through systematic optimization via algorithmic architecture reconstruction and numerical method innovation. The proposed solution involves three key strategies: Firstly, replacing traditional nested-loop programming structures with tensor operations. In a benchmark test case with a 51×51 grid and a pressure relaxation factor of 0.3, the computation time was dramatically reduced from 265.5 seconds to 80 seconds, achieving a speed improvement of approximately 231%. Secondly, an intelligent gradient analysis system was developed using automatic differentiation and dynamic relaxation factors, enabling adaptive adjustment of pressure relaxation factors across grid locations to reduce iteration counts and accelerate computations. Additionally, to overcome the efficiency bottleneck in direct pressure correction value solving, a gradient descent optimization method was employed as an alternative to traditional solvers, further decreasing computational time while enhancing solution accuracy. Validated through standard benchmark cases, the optimized algorithm maintains high precision while significantly improving real-time performance and robustness in complex flow simulations, establishing an efficient and reliable new paradigm for engineering fluid dynamics applications.

Keywords

SIMPLE Algorithm; Tensor Operations; Adaptive Pressure Relaxation; Gradient Descent

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