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基于神经网络的气泡分布超分辨率重建方法研究

摘要

气液两相流气泡空间分布的精确预测在核能装备的设计与运行中至关重要，然而高精度的实验数据和数值模拟数据通常获取难度大，且具有高昂的成本和长时间的计算需求。传统实验方法和数值模拟技术通常只能提供低分辨率的气泡分布信息，难以满足高精度气液两相流研究的需求。为此，本文提出了一种基于神经网络的多尺度超分辨率重建方法，通过训练模型实现低分辨率气泡分布数据的高分辨率重建。结果表明，在 4 倍池化测试算例中，多尺度模型的 MSE 误差低于 0.2%，SSIM 可达 98% 以上。在难度较高的 8 倍池化测试算例中，多尺度模型的 MSE 最高较双三次插值减少 91.9%，SSIM 最高提升 282%，显示出优异的重建效果。本文还探讨了训练集数量对模型性能的影响，发现训练集数量存在一个平稳的转折点，进一步增加数据集规模对模型性能的提升效果逐渐减弱。本文的方法展示了超分辨率重建在气泡分布精细化领域的潜力，为气液两相流的超分辨率重建应用提供了新的研究方向。未来研究可进一步引入物理先验知识，提升模型性能，推动超分辨率技术在复杂气液两相流场中的应用。

关键词

气泡空间分布，超分辨率重建，神经网络，机器学习

Abstract

Accurate prediction of the spatial distribution of gas-liquid two-phase flow bubbles is crucial in the design and operation of nuclear energy equipment, however, high-precision experimental and numeri-cal simulation data are usually difficult to obtain, with high cost and long computation time. Tradition-al experimental methods and numerical simulation techniques can only provide low-resolution bubble distribution information, which is difficult to meet the needs of high-precision gas-liquid two-phase flow research. For this reason, a neural network-based multiscale super-resolution reconstruction method is proposed in this paper, which realizes high-resolution reconstruction of low-resolution bub-ble distribution data by training the model. The results show that in the 4-fold pooling test case, the MSE error of the multiscale model is lower than 0.2%, and the SSIM can reach more than 98%. In the more difficult 8-fold pooling test case, the MSE of the multiscale model is reduced by up to 91.9% compared with double triple interpolation, and the SSIM is improved by up to 282%, showing excel-lent reconstruction results. This paper also explores the effect of the number of training sets on the model performance, and finds that there is a smooth turning point in the number of training sets, and the effect of further increasing the dataset size on the model performance improvement gradually di-minishes. The method in this paper demonstrates the potential of super-resolution reconstruction in the field of bubble distribution refinement and provides a new research direction for the application of super-resolution reconstruction in gas-liquid two-phase flow. Future research can further introduce physical a priori knowledge to enhance the model performance and promote the application of super-resolution technology in complex gas-liquid two-phase flow fields.

Keywords

Bubble Distribution, Super-Resolution Reconstruction, Neural Networks, Machine Learning

Authors: 志远, 孙 (清华大学核研院); Prof. 涵亮, 薄 (清华大学核研院)

Presenter: 志远, 孙 (清华大学核研院)

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