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Boundedness-preserving implicit correction of mesh-induced errors for VOF based heat and mass transfer

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ABSTRACT

Spatial discretisation of geometrically complex computational domains often entails unstructured meshes of general topology for Computational Fluid Dynamics (CFD). Mesh skewness is then typically encountered causing severe deterioration of the formal order of accuracy of the discretisation, or boundedness of the solution, or both. Particularly methods inherently relying on the accurate and bounded transport of sharp fields suffer from all types of mesh-induced skewness errors, namely both non-orthogonality and non-conjunctionality errors.

This work is devoted to a boundedness-preserving strategy to correct for skewness errors arising from discretisation of advection and diffusion terms within the context of interfacial heat and mass transfer based on the Volume-of-Fluid methodology. The implementation has been accomplished using a second-order finite volume method with support for unstructured meshes of general topology. We examine and advance suitable corrections for the finite volume discretisation of a consistent single-field model, where both accurate and bounded transport due to diffusion and advection is crucial. In order to ensure consistency of both the volume fraction and the species concentration transport, i.e. to avoid artificial heat or species transfer, corrections are studied for both cases using distorted 2D meshes. The cross interfacial jump and adjacent sharp gradients of species concentration render the correction for skewness-induced diffusion and advection errors additionally demanding and has not so far been addressed in the literature.

1. Introduction

Algebraic Volume-of-Fluid (VoF) methods [1–4] are widely used for numerical simulations of flows consisting of two incompressible fluid phases with a sharp deformable interface separating them. Recently a model for interfacial species transfer within the algebraic VoF framework, namely the Continuous Species Transfer (CST) model, was presented in [5,6]. Within this modelling framework, heat transfer is to be seen as a special case without jump and can thus be described by a simplified CST model equation. Both methods, VoF and CST, are derived by applying the Conditional Volume-Averaging (CVA) technique to the local instantaneous sharp interface model equations and the corresponding interfacial jump conditions so

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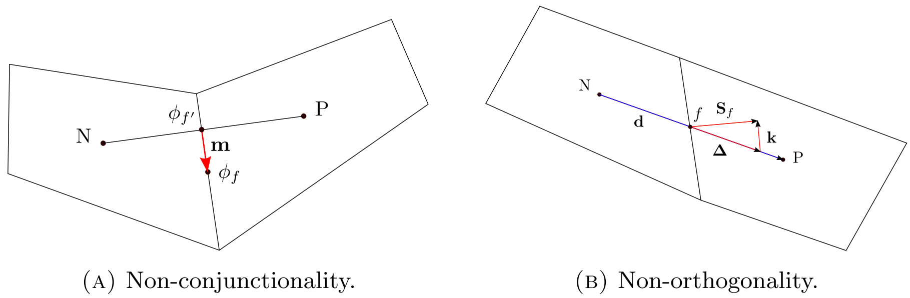

Fig. 1. Types of mesh skewness.

as to transform them into volume-averaged single-field equations. In this form the governing equations are readily suitable for consistent discretisation using a Finite Volume Method (FVM).

When considering computational domains entailing complex geometries, unstructured meshes of general topology are required. Then, depending on the mesh quality, discretisation errors related to mesh skewness arise and can severely deteriorate the numerical fidelity of the method resulting in loss of boundedness, accuracy and order of convergence. Typically, two types of skewness errors are to be distinguished: errors due to non-conjunctionality and errors due to non-orthogonality at the three-point stencil around a cell face (see Fig. 1). In order to avoid deterioration of numerical fidelity on such meshes, skewness correction approaches have been devised for FV discretisation and are nowadays well established practice. Classical approaches are explicit and correct for non-orthogonality during discretisation of diffusion terms and non-conjunctionality during FV discretisation of advection terms, respectively. For an overview of state-of-the-art classical approaches to skewness correction the interested reader is referred to [7–9]. A non-classical explicit approach is the ghost-point method set out by Perić in [8], correcting for both non-conjunctionality and non-orthogonality simultaneously.

Applying classical (explicit) skewness correction approaches to the VoF advection equation on distorted meshes results directly in severe unboundedness of the volume fraction and as a consequence in substantial problems with stability and/or accuracy. The reason for this resides in the fact that due to the typically high density ratios even small errors in the volume fraction cause large errors in mass fraction and consequently in the momentum. It has been found that in such cases implicit correction approaches are needed, see [10–12] and more recently [13,14]. Taking interfacial heat and mass transfer into consideration renders the situation even more challenging, since there are now both the discretised advection and diffusion terms to be skewness corrected. While it is obvious that classical explicit approaches remain unsuitable (likewise causing unboundedness errors as for the VoF transport), up to now it is unclear whether implicit correction approaches can be used to correct for mesh skewness when applied to the discretised form of the CST model for interfacial heat and mass transfer.

This contribution is concerned with enhancements of implicit correction approaches based on a detailed investigation into their suitability to maintain numerical fidelity such as boundedness, accuracy and order of convergence in the context of VoF/CST-based simulations of interfacial heat and mass transfer on distorted meshes of general topology. In contrast to previous work, we introduce implicit skewness corrections for finite volume discretisations of both advection and diffusion terms. Moreover, we use finite volume meshes which have been distorted in a targeted manner rather than randomly (as is common practice in the existing literature) in order to allow a systematic study on mesh-induced errors and avoid error cancellation. The objectives of this work are two-fold, viz.

- To devise a suitable method for mesh skewness correction for the discretised advection and diffusion terms of the single-field CST model for VoF-based interfacial heat and mass transfer. Notably, one of the CST model terms is discretised in a non-standard way [6], that is, despite originating from a diffusive transport term, it has been found that it is best to treat one term implicitly by means of a FV divergence rather than a FV laplacian operator.
- To identify and clarify the influence of a jump in the scalar transport variable on the order of convergence when refining a systematically distorted finite volume mesh and applying implicit skewness corrections.

This study has been accomplished using and extending OpenFOAM (version 4.x).

2. Standard finite volume discretisation and mesh-induced errors

In order to better understand the proposed approach to implicit skewness correction for VoF/CST-based interfacial heat and mass transfer on distorted meshes of general topology, the errors on skewed meshes in finite volume discretisation of a prototypical scalar advection–diffusion equation are briefly recapped and a review of prominent publications addressing these errors is given.

The starting point of our investigations is the advection–diffusion equation for an arbitrary scalar quantity ϕ and a scalar diffusive coefficient Γ_ϕ, i.e.