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Dynamic Modeling of Phase Crossings in Two-Phase Flow

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Abstract. Two-phase flow and heat transfer, such as boiling and condensing flows, are complicated physical phenomena that generally prohibit an exact solution and even pose severe challenges for numerical approaches. If numerical solution time is also an issue the challenge increases even further. We present here a numerical implementation and novel study of a fully distributed dynamic one-dimensional model of two-phase flow in a tube, including pressure drop, heat transfer, and variations in tube cross-section. The model is based on a homogeneous formulation of the governing equations, discretized by a high resolution finite difference scheme due to Kurganov and Tadmore.

The homogeneous formulation requires a set of thermodynamic relations to cover the entire range from liquid to gas state. This leads a number of numerical challenges since these relations introduce discontinuities in the derivative of the variables and are usually very slow to evaluate. To overcome these challenges, we use an interpolation scheme with local refinement.

The simulations show that the method handles crossing of the saturation lines for both liquid to two-phase and two-phase to gas regions. Furthermore, a novel result obtained in this work, the method is stable towards dynamic transitions of the inlet/outlet boundaries across the saturation lines. Results for these cases are presented along with a numerical demonstration of conservation of mass under dynamically varying boundary conditions. Finally we present results for the stability of the code in a case of a tube with a narrow section.

AMS subject classifications: 76T10, 80A20, 65M06

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1 Introduction

Simulation of two-phase flow and heat transfer is important for the analysis of a range of fundamental physical processes and phenomena such as evaporation and condensa-

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tion. Thus, the application of numerical methods has a substantial impact on research and development within a large range of industrial applications, for example, the design of heat exchangers in areas of power generation, refrigeration and air conditioning, industrial thermal- and chemical process plants. As the requirements of these industrial applications tend towards increasing energy efficiency, the requirements for model accuracy and stability of the numerical tools increase. Consequently there is a growing need for more detail in the modeling of the basic phenomena while at the same time keeping the computation efficient.

Computationally demanding components in the systems mentioned above are mainly the dry-expansion evaporators in refrigeration and air-conditioning systems. Lumped component models for these components are traditionally solved using NTU-ϵ - methods or models of the moving boundary type [1–4]. Such models have an advantage by realistically demonstrating dynamical behavior of the component in relation to capacities, temperature, and pressure levels although formulated as lumped models. A disadvantage is a loss of detail in the modeling and the handling of fluid-zone switching which may result in numerical instability and increased computation time.

In a general effort to investigate the dynamic behavior of two-phase flow and heat transfer we are seeking a mathematical formulation that provides a stable numerical solution despite the problem involves a dynamically changing number of fluid zones [5]. Several works have been published on fully distributed models solving the governing equations [6–9]. However, the fast pressure dynamics of the full set of governing equations is neglected in earlier analyses in order to accomplish faster computation times and numerically stable codes. Also, these earlier models are generally limited to constant cross sectional area of the tubes

To handle the above difficulties, high resolution difference schemes have been developed as "black box" solvers for both conservation laws and Hamilton-Jacobi equations [10, 11]. In the semi-discrete form, they are easily implemented using, e.g., Runge-Kutta methods for ordinary differential equations, and therefore an attractive alternative to commercial CFD codes. Applications of high resolution difference schemes to two-phase flow problems include the so-called separated models where liquid and gas are treated as two separate fluids [12]. In these models, interphase exchange terms are needed to model the evaporation/condensation process and the form of the terms depends on the two-phase flow regime [13]. In the homogenous formulation, these details are instead included in the thermodynamic relations available from, for example, the National Institute of Standards and Technology [14].

In this paper, we develop a novel numerical model to effectively handle the fast dynamics and the associated phenomena when crossing the phase boundaries. We present the application of the Kurganov-Tadmor (KT) semi discrete central difference method [10, 11] to the case of two-phase boiling flow in a single tube exchanging heat with the surroundings. The model is derived for a tube of arbitrary cross section.