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Fully implicit numerical simulation of subcooled flow boiling in a vertical channel using higher order schemes

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Abstract

In this paper, a numerical method for unsteady subcooled flow boiling based on the quasi-homogeneous flow model (QHFM) is presented. Finite volume techniques based on the staggered mesh are used for spatial discretization and ESDIRK scheme is administered to achieve arbitrary high order of temporal accuracy. The nonlinear equations are solved by the Newton-Krylov method. To validate the method, the predicted results are compared with the experimental data and a good agreement is found between the results. The numerical results show that the use of higher order schemes leads to more accurate consequences. Also for each scheme, the smaller the time step the more accurate the predicted results. The effect of using higher order methods in reducing the cost of computations was investigated and we found that the cost of computation significantly reduced using the ESDIRK schemes.

Keywords: Fully implicit; Subcooled flow boiling; Higher order scheme; Two-phase flow

Introduction

Simulation of the two-phase flow plays a crucial role in nuclear reactor safety. The mathematical description of the unsteady two-phase flow is provided with a set of PDE equations. Mathematical models are used to discretize a set of PDE equations in space and time. The finite volume method is usually used for spatial discretization of the governing equations [1]. For temporal discretization, the backward or forward Euler method (first order or second order accuracy in time) are well known and widely used.

In two-phase flow problems, the time step size is small [2]. In order to take larger time steps without decreasing the temporal accuracy, a higher order time discretization scheme is proposed.

Many researchers applied the implicit RK methods to unsteady flows. Bijl et al. [3, 4] studied different time integration methods for unsteady 2-D laminar fluid around a cylinder. In these work Bijl and coworkers focus on the explicit first stage singly diagonally implicit Runge-Kutta (ESDIRK) scheme that is a subset of the RK methods. Ijaz and Anand [5] presented the SIMPLE-ESDIRK scheme for the unsteady incompressible, viscous 2-D fluids. Also, Lopez et al. [6] developed a numerical method based on the ESDIRK scheme to model 1-D subcooled boiling two-phase flow in the upward flow channel. They used the quasi-homogeneous flow model (QHFM) to describe the two-phase flow model and at each stage the pressure correction equation was obtained by the SIMPLE algorithm. In summary, a combination of SIMPLE algorithm and ESDIRK method was introduced for simulation of the subcooled flow boiling. The result of this research is that although the SIMPLE method is an accurate method, however, to get the right answer, the code needs a lot of iterations for convergence. The CPU time of the above method is also high, this is an important problem especially for modeling transient flow where CPU time is the main matter. To solve these problems, we need more efficient computational scheme in order that with less computational cost, an acceptable response achieved.

Physical model and solution methods

In the present study, a numerical method for the unsteady subcooled flow boiling based on the quasi-homogeneous flow model is presented. At present, the work focuses on the use of the implicit high-order RK methods in relation to the Newton-Krylov scheme. In this procedure, different ESDIRK schemes to achieve the arbitrary higher order of the temporal accuracy is used and the resulting nonlinear equations are solved by the Newton-Krylov method. The key to success of the JFNK is an efficient preconditioning of the GMRES. Therefore, a generalized minimal residual (GMRES) scheme [7] as the Krylov method for solving the 1-D QHFM in the two-phase fluid problem in a vertical channel is presented. Likewise, an incomplete LU factorization with the dual truncation (ILUT) scheme is used to precondition the Krylov solver GMRES.

In the present study the conservation equations assumed quasi-homogeneous, incompressible flow. It should be noted that, while quasi-homogeneous flow model (QHFM) has a wide range of applicability, there are certain limitations in the developed method due to its mathematical formulation and implemented correlations. The QHFM formulation is not sufficient for cases with large relative phase velocities, counter-current flow, or condition where the flow regime changes radically.

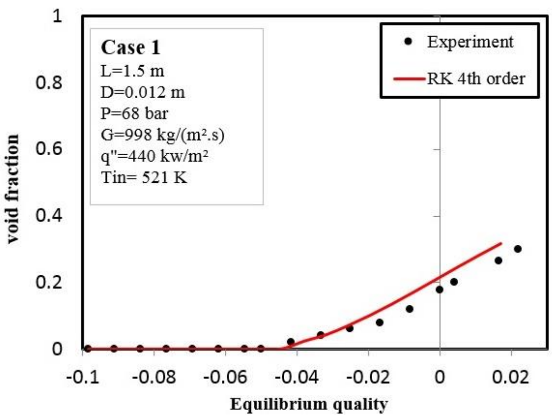

Fig.1. Comparisons of results

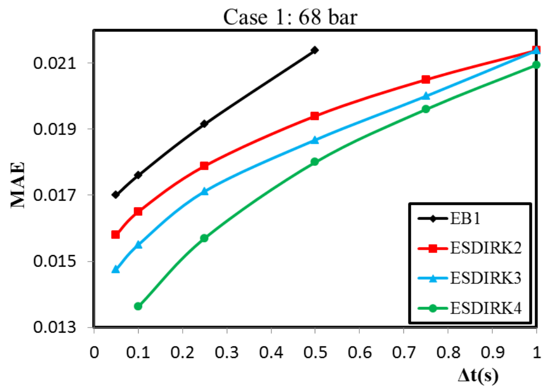

Fig. 2. Variation of MAE vs. time step (Δt)

Results and discussion

To confirm the analytical capability and effectiveness of the present method, the present method has been applied to experimental test Bartolomei and Chanturiya [8]. This experiment covers a wide range of conditions. Fig. 1 shows a comparison of the numerical results (void fraction vs. quality) of the present method obtained by RK 4th order method and the experimental data for the cases studied.

Fig. 1 shows that there is a good agreement between the numerical results and experimental data. Fig. 1 illustrated that for a wide range of pressures and different working conditions, the present model can provide accurate and reliable results.

Fig. 2 displayed that for smaller time steps, the slope of the diagrams is greater this means that for smaller time steps, the error decreases faster. Furthermore, the high-order RK multistage schemes (ESDIRK methods) have different effects on different cases. For example, for case 1 (68 bar) and with the ESDIRK4 procedure and with a time step of dt =0.4 the void fraction MAE 0.01 is obtained, while the EB1 approach to achieve the same accuracy requires dt=0.05. Notice that the size of time step used by the ESDIRK4 method is eight times the Euler's method.

Conclusions

The results of the calculation obtained by the proposed method showed good agreement with the experimental data. In order to calculate the error between the computational results and the experimental data, the void fraction MAE versus the time step is also evaluated. It was found that the use of higher order schemes such as ESDIRK4 leads to more accurate results. Furthermore, the use of the ESDIRK4 method makes it possible to use the time step eight to thirteen times larger than Euler method, but the same precision is achieved. For all schemes, It was found that the smaller the time step, the more accurate the results.

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