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Accurate Prediction of Transitional Flows among Gas, Liquid and Supercritical Fluids

***Takashi Furusawa and Satoru Yamamoto**

Department of Computer and Mathematical Sciences, Tohoku University
6-6-01 Aobayama, Aoba-ku, Sendai 980-8579, Japan
E-mail yamamoto@caero.mech.tohoku.ac.jp and URL www@caero.mech.tohoku.ac.jp

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ABSTRACT

A numerical method for simulating transitional flow problems among gas, liquid and supercritical fluids is presented. This method is based on the preconditioning method developed by the authors[1] and is fully coupled with the database of thermo-physical properties of fluids, PROPATH, developed by Kyushu university[2]. The present preconditioning method is based on a compressible flow solver and it employs a preconditioned flux-vector splitting(PFVS) scheme[1]. The PFVS enables us to calculate not only high-speed flows but also flows at very low Mach number.

We know a number of substances such as water, carbon-dioxide, oxygen, nitrogen, and so on. These substances have their own thermo-physical properties. Those properties are changed according to bulk conditions. Unfortunately, all the existing CFD solvers assuming ideal gas or incompressible fluids cannot calculate such a real flow problems. In PROPATH, thermo-physical models for 48 substances are programmed in wide-range pressure and temperature conditions. PROPATH can cover all states such as gas, liquid and supercritical states except for solid. Each model is defined as a function of pressure and temperature. All the thermo-physical properties used in the present method employ the functions defined in PROPATH. The functions for a substance can be referred from PROPATH when the present code is compiled with the library file, *.lib for the substance. The substance is easily changed to a different substance only if the library file is changed to that for the different substance. For example, equation of state(EOS) for carbon-dioxide was standardized by International Union of Pure and Applied Chemistry(IUPAC)[3]. The EOS model is defined by

$$p = \rho RT\left[1 + \omega \sum_{i=0}^{9} \sum_{j=0}^{J_i} a_{ij} \left(\tau - 1\right)^j \left(\omega - 1\right)^i \right] \qquad (1)$$

where $\omega = \rho / \rho^*$, $\tau = T^* / T$. Actually in this case , $\rho^* = 468\,[\mathrm{kg/m^3}]$, $T^* = 304.21$ [K]. a_{ij} and J_i are defined in IUPAC. Thermo-physical properties such as specific heat at constant volume and that at constant pressure can be derived using Eq.(1). These values are theoretically defined by

$$C_v = \int_0^{\rho} \frac{T}{\rho^2} \left(\frac{\partial^2 p}{\partial T^2} \right)_{\rho} d\rho + C_v^{ideal} \ , \quad C_p = C_v + \frac{T}{\rho^2} \frac{\left(\partial p / \partial T\right)_{\rho}^2}{\left(\partial p / \partial \rho\right)_T} \qquad (2)$$

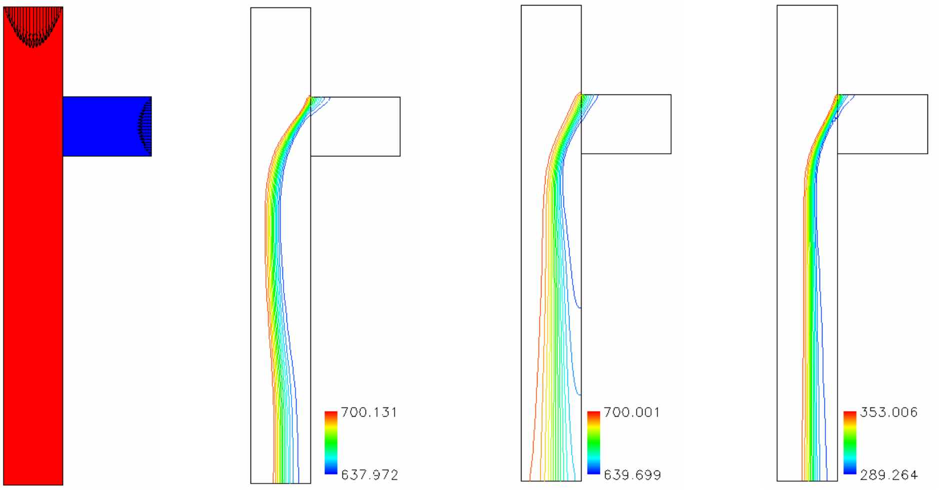
where C_v^{ideal} is the specific heat at constant volume for ideal gas. Other thermo-physical properties such as the coefficient of heat conduction and that of molecular viscosity are defined by their own equations based on a polynomial equation. Also those for other substances are defined in a similar manner.

In this paper, the present method is applied to the simulation for flows of arbitrary substance in arbitrary conditions, especially these transitional flows in both supercritical state and gas or liquid state in a same flow field.

As numerical examples, the calculated result of a transitional flow of water in supercritical and liquid states through a T-shaped channel is only explained here. The flow schematic is shown in Fig.1(a). A laminar flow is assumed. The red-colored channel is a main channel and the blue-colored channel is a sub-channel connected to the main channel. Inlet temperature and the pressure of the main channel are fixed to 700[K] and 30[MPa]. These values indicate that the flow incoming to the main channel is in a supercritical condition. Inlet temperature of the sub-channel is 640[K] and the pressure is the same value with that of the main channel. The flow incoming to the sub-channel is in a liquid condition. Therefore, the supercritical water through the main channel is to be interacted with the water liquid from the sub-channel.

Figure 1(b) shows the calculated temperature contours. The water liquid is encountered at the T-junction and the supercritical water and the water liquid stream downward together. The contours of temperature seem to be concentrated near the flow mixing region quite locally. In this region, the critical region between the supercritical water and the water liquid is certainly located. Such a transitional region where thermo-physical properties are changed rapidly can be captured stably by the present method.

Figure 1(c) shows the calculated temperature contours of the flow in a whole gas condition. The bulk pressure is reduced to 10[MPa]. Also the case of whole liquid is shown in Fig.1(d). It has an atmospheric water-liquid condition. As compared with Figs 1(c) and 1(d), the temperature shown in Fig.1(b) has its unique distribution. Other thermo-physical properties obtained in these cases have been also compared with each other. The detail will be explained in the final paper with those for other flow problems.



(a) Schematic (b) Transitional flow (c) Gas flow (d) Liquid flow

Fig.1 Flow schematic and the calculated temperature contours

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