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Single- and two-fluid models for steam condensing flow modeling

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ABSTRACT

The paper presents a description of two models dedicated to steam condensing flow modeling. The models are implemented into an in-house computational fluid dynamics (CFD) code that has been successfully applied to a wet steam flow calculation for many years now. Both models use the same condensation model that has been validated against the majority of available experimental data. The state equations for vapor and liquid water, the physical model as well as the numerical techniques of solution to flow governing equations have been presented. For the single-fluid model (SFM), the Reynolds-averaged Navier–Stokes (RANS) equations for vapor/liquid mixture are solved, whereas the two-fluid model solves separate flow governing equations for the compressible, viscous and turbulent vapor phase and for the compressible and inviscid liquid phase.

Both described models have been compared with relation to the flow through the Laval nozzle.

1. Introduction

Nowadays efforts are made to improve the efficiency of fossil fuel power plants even by more than 50%. It is connected with the implementation of new ultra-supercritical technologies and an ongoing push to reduce stack emissions of all pollutants and to capture CO_2. The steam turbine is the main facility of a power plant and improvement in its efficiency will produce significant economic benefits.

The low-pressure turbine blades are one of the most important components in the overall steam turbine design. A fully developed 3-D stage flow analysis can provide an optimum blade profile capable of minimizing the losses from shock waves resulting from the supersonic flow. The accuracy of the modern 3-D analysis as a prediction tool has improved considerably and it can now account for non-equilibrium condensation flows with different steam wetness conditions and phase change variations (Heiler, 1999; Stastny and Sejna, 2005; Dykas et al., 2007).

The steam temperature in low-pressure turbines decreases due to expansion. In turbines of large output the superheated vapor usually crosses the saturation line in penultimate stages. At least the last two stages of the low-pressure turbine operate in the two-phase region producing much more than 10% of the total output. The presence of the liquid phase within the turbine causes thermodynamic losses (caused by the internal heat transfer within the fluid), aerodynamic losses (losses that occur due to the interaction of the fluid with the walls and caused by aerodynamic shocks) and mechanical losses or erosion (droplet impingement on the blades damages the steam turbine blades). Therefore, any decrease in them is worth striving for.

The homogeneous condensation phenomenon was already investigated experimentally and numerically many year ago (e.g. Gyarmathy, 1960; Puzyrewski, 1969; Schnerr, 1986). However, the effective numerical algorithms that could be used for a prediction of the wet steam flows in turbine cascades have been developed and perfected for last 20 years.

Also the heterogeneous condensation on soluble or insoluble impurities plays an important role in the liquid formation in a condensing steam turbine (Wróblewski et al., 2009b), but due to the lack of experimental data for heterogeneous condensation in the first step the homogeneous condensation will be considered in this work only.

There are two main kinds of numerical models of the wet steam flow with homogeneous condensation which can be applied to the flow field modeling in LP stages. One includes the single–fluid model (SFM) and is called a no-slip model. The other is a two-fluid model (TFM) taking into account the velocity slip between the vapor and the liquid phase.

Modeling of steam homogeneous condensation has been investigating in thermodynamic and gas dynamic aspects by numerous authors for many years now (Halama et al., 2010). The first numerical predictions of the condensing steam flow were focused on one-dimensional flow in the Laval nozzle using linearized equations (e.g. Puzyrewski, 1969). A lot of experimental data for the flow in the Laval nozzle and 2D blade cascades have been contributed to the validation of the CFD methods with implemented various condensation models (White et al., 1996; Bakhtar et al., 2005; Heiler, 1999), but mainly SFM models. These models seemed to be well-suited for modeling the wet steam flow in real turbine stages

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(Dykas et al., 2007, Wroblewski et al., 2009a,b) to determine both thermodynamic and aerodynamic losses.

However, in order to predict mechanical losses, especially the trajectory of liquid droplets and their possible impingement on the blade surface, a two-fluid model has to be applied, in which the velocity slip between the phases is taken into account. It allows better understanding the processes of the blade surface deterioration. Two-fluid models for such type of flow are much more complicated and, consequently, much less popular.

The aim of this paper is to present a description of the models for the wet steam flow field prediction which could be employed for losses estimation, and further – for efficiency improvement of the last LP turbine stages. Presented work focuses on an accuracy assessment of the SFM and TFM models with respect to modeling of the place and intensity of homogeneous condensation.

These models are implemented into an in-house CFD code used for many years at the Institute of Power Engineering and Turbomachinery of the Silesian University of Technology in Gliwice for engineering applications.

2. Physical model

Steam with high velocity in low-pressure stages achieves a supercooled state and then the subcooled vapor loses its latent heat L, and liquid droplets with small diameters are formed. Next, depending on the thermodynamic conditions these small droplets grow or vanish. Hence, the numerical algorithm modeling such flow must solve the equations governing the compressible flow supplemented by the real gas equation of state, and the algorithm should include additional relations describing phase transitions.

For simplicity it was assumed that the two phases are governed by the same averaged pressure:

$$p = p_v = p_l \tag{1}$$

The following relationships connect the liquid and the vapor phase:

$$\begin{aligned} \alpha &= \frac{V_l}{V_m} \\ \rho_m &= (1-\alpha)\rho_v + \alpha\rho_l \\ h_m &= (1-y)h_v + yh_l \\ y &= \alpha\frac{\rho_l}{\rho_m} \end{aligned} \tag{2}$$

where α is the volume fraction and y is the mass fraction of the liquid phase. The density of the mixture ρ_m, is a function of vapor density ρ_v, liquid density ρ_l, and α. The enthalpy of mixture h_m, is determined in a similar way. Mass fraction y depends on the volume fraction as well as on the ratio between the liquid and the mixture density, and for the presented problem has a value by approx. 10^3 higher than the volume fraction.

3. Auxiliary relations

3.1. Equation of state for vapor

There are many forms of real gas equations of state for steam known from literature. At the moment, the most accurate and widely used and the most recommended for industrial use is the "IAPWS Industrial Formulation 1997" (IAPWS-IF97). The IAPWS Industrial Formulation 1997 consists of a set of equations for different regions. The basic equation for each region is a fundamental equation for the specific Gibbs free energy. This equation has a very complicated form and is practically useless for a direct application into CFD codes. In the presented in-house CFD code the 'local' real gas state equation was used in a form similar to the virial equation of state with one virial coefficient (Dykas, 2001):

$$\frac{p}{RT\rho_v} = z(T,\rho_v) = A(T_v) + B(T_v)\rho_v \tag{3}$$

where p, v, T are pressure, specific volume and temperature, respectively, $R = 461.5$ J/kg K is the gas constant, z stands for the compressibility coefficient and polynomials $A(T)$, $B(T)$ are defined as:

$$A(T) = a_0 + a_1 T + a_2 T^2$$

$$B(T) = b_0 + b_1 T + b_2 T^2$$

Coefficients a_i, b_i $(i = 0, \ldots, 2)$ of polynomials $A(T)$ and $B(T)$ are the functions of temperature only, and they are calculated from an approximation of the thermodynamic properties of steam following the IAPWS-IF97 formulas.

Due to its simple form, the solution to the flow governing equations is obtained relatively fast, but it is still necessary to solve the non-linear equations to determine the primitive variables from the conservatives ones. The applied simple mathematical form of the EOS can be very accurate, but only for a limited range of parameters (Fig. 1).

The rest of the thermodynamic properties of the vapor phase are calculated on the basis of the applied state Eq. (3).

3.2. Equation of state for liquid

While considering water under the conditions close to the saturation line for pressure smaller than 1 bar, the IAPWS-IF97 formulation can be used as well, where the liquid water properties like temperature, density, enthalpy and speed of sound c can be determined from the following functions:

$$\begin{aligned} T_l &= T_l(p,h_l) \\ \rho_l &= \rho_l(p,T_l) \\ h_l &= h_l(p,T_l) \\ c_l &= c_l(p,T_l) \end{aligned} \tag{4}$$

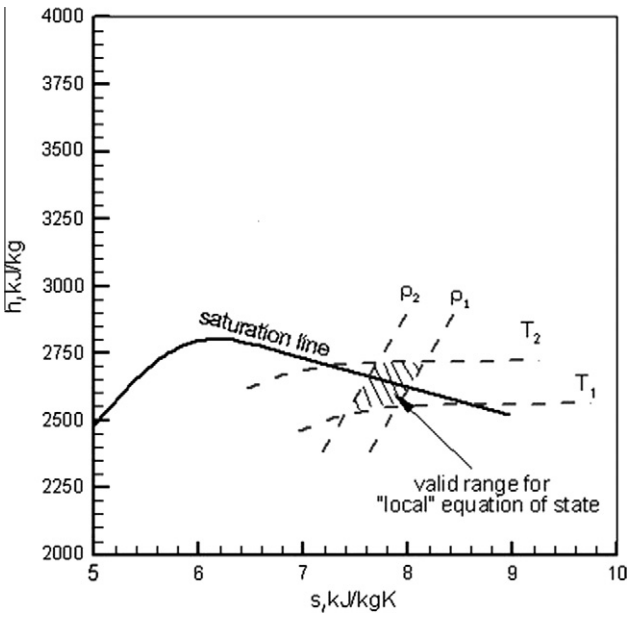

Fig. 1. Mollier diagram of the "local" real gas equation of state near the saturation line.