Energy 106 (2016) 112–120

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Two-fluid model with droplet size distribution for condensing steam flows

Włodzimierz Wróblewski, Sławomir Dykas*

Institute of Power Engineering and Turbomachinery, Silesian University of Technology, Gliwice, Poland

ARTICLE INFO

Article history:
Received 19 September 2015
Received in revised form
25 February 2016
Accepted 12 March 2016
Available online 1 April 2016

Keywords:
Steam turbine
Wet steam
Condensation
Polydispersed two-fluid model

ABSTRACT

The process of energy conversion in the low pressure part of steam turbines may be improved using new and more accurate numerical models. The paper presents a description of a model intended for the condensing steam flow modelling. The model uses a standard condensation model. A physical and a numerical model of the mono- and polydispersed wet-steam flow are presented. The proposed two-fluid model solves separate flow governing equations for the compressible, inviscid vapour and liquid phase. The method of moments with a prescribed function is used for the reconstruction of the water droplet size distribution. The described model is presented for the liquid phase evolution in the flow through the de Laval nozzle.

1. Introduction

In high-capacity condensing turbines the stages of low pressure part steam turbine operating in the wet steam region are responsible for about 10% of the total power generated by the turbine. Their efficiency is substantially lower than the efficiency of stages operating in the superheated steam region. The impact of internal efficiency of the last stages of the turbine low pressure part on the efficiency of the entire cycle is estimated at the level of even several percentage points. Therefore, any improvement therein may bring about a considerable increment in the efficiency of the total system generating electricity or heat. The steam turbine flow path can be improved using new and more accurate computational models. When it comes to the search for the potential for improvements in the energy conversion efficiency, it is the turbine low-pressure part stages that are particularly interesting. In stages where expansion occurs below the saturation line, the two-phase flow takes place with all the physical phenomena related thereto, such as the occurrence of a non-equilibrium process of steam condensation. Steam condensation during expansion in the turbine stage results in additional thermodynamic and kinematic losses.

A very important item of information in the two-phase flow calculations are the parameters of the dispersed phase size distribution. The change in steam parameters in the process of the liquid phase formation is strongly dependent on the flow dynamic phenomena and vice versa, which has an effect on the shape of the droplet size distributions. In the case of steam flows in the steam turbine, the droplet size distribution constitutes essential information for the designer as it indicates the need to adopt additional solutions improving the reliability and durability of the turbine flow part components. The problem concerns the use of the liquid phase separation system, protection of places in the flow system which are most exposed to erosion as well as the issue of matching the flow system geometry to the kinematics of the dispersed phase flow.

Despite the considerable progress made in the development of the CFD (Computational Fluid Dynamics) computational methods, modelling the two-phase flow in the turbine blade-to-blade cascade remains a complex task. Wet steam flow modelling is still a current issue taken up all over the world. The Cambridge University centre presents progress made in theoretical studies of water vapour flows in a series of papers concerning the extension of the computational algorithm by the viscous gas model [1] and by the polydispersed model which can be applied in the Euler–Lagrange description of the liquid phase flow [2]. An interesting survey of selected works concerning the research on wet steam was presented by Bakhtar [3]. He drew attention to the confirmed, substantial share of thermodynamic losses resulting from water vapour condensation in the total loss value. He also indicated the impact of the size and number of droplets arising due to primary and secondary nucleation on the volume of losses.

* Corresponding author.
E-mail address: slawomir.dykas@polsl.pl (S. Dykas).

http://dx.doi.org/10.1016/j.energy.2016.03.052
0360-5442/

Many works on modelling the water vapour flow focus on considering the droplet size distribution, for example Gerber's studies [4,5], White's works [6,2] or works by Halama and Fort [7]. Describing the droplet distribution, they all used the transport equation for the dispersed phase size according to the concept presented by Hill [8]. In their calculations, all these approaches draw on the assumption of no slip between the phases. A proposal was put forward to extend this method for aerosol flows, taking the slip between the phases into consideration [9]. The possibility of analysing two-phase systems with different velocities of the phases and different temperatures is discussed in the work of Zywotiagin et al. [10], where the conditions for the Godunov method application are defined and a one-dimensional analysis of a sudden outflow of water with high parameters is presented. The objectives formulated in this paper constitute the completion and extension of previously conducted analyses in both the methodological and the practical aspect. The computational algorithms for the modelling of the steam flow with a non-equilibrium condensation process developed in the Institute of Power Engineering and Turbomachinery take account of the existence of a condensation zone in a turbine stage. The presence of the liquid phase changes the flow kinematic parameters in the stage and the volume of losses [11,12]. Such a model assumes that the droplets are small enough to omit the phenomenon of the slip between the phases. However, this simplification makes it impossible to take account of the real movement of the droplets in the flow channel. Therefore, a two-fluid flow model was developed in which systems of conservation equations formulated for the liquid and the gaseous phase are solved [13,14]. The model takes account of the slip between the phases, assuming the mean radius of droplets. Such an approach provides more information about the two-phase flow, but it may not be used, for example, to assess the erosion process.

This paper extends the condensing steam flow model by introducing equations governing the droplet size distribution into the slip model. Here, the liquid phase equations are written in the form of what is referred to as moment equations. The calculation results are presented for the flow through the de Laval nozzle for geometrical data and boundary conditions tested experimentally [15] and commonly used to verify calculation results.

2. Governing equations

2.1. Monodispersed model

The nozzle steam flow was analysed using the compressible inviscid fluid model. The following relations between the water and steam quantities apply to the mixture:

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

where α and y are the liquid phase volume and mass content, respectively. The mixture density ρ_m is a function of steam density ρ_v, water density ρ_l and α. The mixture specific enthalpy h_m is defined in a similar manner from the steam and water specific enthalpy h_v and h_l. The liquid phase mass content (the moisture degree) y depends on the volume content and on the water-to-mixture density ratio. In the case under analysis, the mass content values are about 10^3 times higher than those of the volume content.

In the applied slip model, taking the difference between the gaseous and the liquid phase into consideration, the conservation equations are formulated separately for each phase. Neither the interaction between droplets nor the heat flux between the liquid phase and the flow channel walls are modelled.

For the inviscid fluid model the conservation equations for the gaseous phase are expressed in the following way:

$$\begin{aligned}
&\frac{\partial(\rho_v(1-\alpha))}{\partial t} + \frac{\partial\left(\rho_v(1-\alpha)u_{vj}\right)}{\partial x_j} = -\Gamma_1 - \Gamma_2 \\
&\frac{\partial(\rho_v(1-\alpha)u_{vi})}{\partial t} + \frac{\partial\left(\rho_v(1-\alpha)u_{vj}u_{vi} + (1-\alpha)p_v\delta_{ij}\right)}{\partial x_j} = -\Gamma_2 u_{int\,j} \\
&-F_{Dj} - p_{int}\frac{\partial\alpha}{\partial x_j} \\
&\frac{\partial(\rho_v(1-\alpha)E_v)}{\partial t} + \frac{\partial\left(\rho_v(1-\alpha)u_{vj}H_v\right)}{\partial x_j} = -\Gamma_2(H_{vint} - L) \\
&-u_{int\,j}F_{Dj} - p_{int}u_{int\,j}\frac{\partial\alpha}{\partial x_j}
\end{aligned} \tag{2}$$

where:

$$E_v = h_v - \frac{p_v}{\rho_v} + \frac{1}{2}u_{vj}u_{vj} = H_v - \frac{p_v}{\rho_v},$$

and L denotes latent heat, which may be found based on values of the steam and water specific enthalpy in saturation conditions.

The liquid phase for the monodispersed model is described by the following conservation equations:

$$\begin{aligned}
&\frac{\partial(\rho_m n)}{\partial t} + \frac{\partial\left(\rho_m n u_{lj}\right)}{\partial x_j} = J\rho_m \\
&\frac{\partial(\rho_l\alpha)}{\partial t} + \frac{\partial\left(\rho_l\alpha u_{lj}\right)}{\partial x_j} = \Gamma_1 + \Gamma_2 \\
&\frac{\partial(\rho_l\alpha u_{li})}{\partial t} + \frac{\partial\left(\rho_l\alpha u_{lj}u_{li} + \alpha p_l\delta_{ij}\right)}{\partial x_j} = \Gamma_2 u_{int\,j} + F_{Dj} + p_{int}\frac{\partial\alpha}{\partial x_j} \\
&\frac{\partial(\rho_l\alpha E_l)}{\partial t} + \frac{\partial\left(\rho_l\alpha u_{lj}H_l\right)}{\partial x_j} = \Gamma_2 H_{lint} + u_{int\,j}F_{Dj} + p_{int}u_{int\,j}\frac{\partial\alpha}{\partial x_j}
\end{aligned} \tag{3}$$

where

$$E_l = h_l - \frac{p_l}{\rho_l} + \frac{1}{2}u_{lj}u_{lj} = H_l - \frac{p_l}{\rho_l}.$$

For reasons of simplicity it is assumed that both phases are characterized by identical pressure $p = p_v = p_l = p_{int}$. The first equation in the system of Eq. (3) is added to the liquid phase equations to balance the droplet number in the flow field. The equation is referred to as the population balance equation and concerns the number of droplets with a mean radius.

In Eqs. (2) and (3), u_{intj} denotes the interphase velocity component, which for well-mixed phases may be determined from the following relation:

$$u_{int\,j} = \frac{\rho_l u_{lj}\alpha + \rho_v u_{vj}(1-\alpha)}{\rho_m} \tag{4}$$