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Numerical solution of transonic flow of steam with non-equilibrium phase change using typical and simplified method

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ABSTRACT

Simulation of transonic flow of steam with phase changes represents rather complex problem. One has to consider several simplifications to obtain a flow model, which is computationally adequate. Typical current simulations are based on the solution of transport equations for the mixture and additional transport equations for the liquid phase. The creation of new droplets and the growth of already existing droplets is included in the form of source terms, which require a special treatment for time integration. The aim of this paper is to compare an alternative simplified method with a typical method. The alternative simplified method uses no additional transport equations and the non-equilibrium phase change is included in a form of switch from the metastable state to the equilibrium state, i.e. switch from the zero to the equilibrium wetness. Although this simplified method cannot provide details about droplet size, it can still be interesting tool for the early steps of the turbine design. Both methods are based on the numerical solution of governing equations using a finite volume method. The advantages and disadvantages of simplified method with respect to typical method are discussed and demonstrated on simulations of flow in nozzle and turbine cascades.

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1. Introduction

The condensation of water vapor during an expansion is one of the important phenomena, which should be considered for steam turbine flow simulations. The condensation usually does not follow the equilibrium thermodynamic model and starts later when sufficient vapor sub-cooling is reached. Therefore non-equilibrium condensation models, which take into account this delay, provide results more close to reality. Some comparisons between equilibrium and non-equilibrium models can be found in [9] or [27]. The start of non-equilibrium condensation is characterized by intensive nucleation connected with intensive latent heat release, which considerably decreases the vapor sub-cooling. The nucleation is concentrated into small area and has non-negligible influence on the flow field. Numerical simulations thus requires careful discretization especially within the nucleation zone as well as proper combination of nucleation and droplet growth models to avoid errors in the prediction of the amount and size of new droplets. The nucleation is followed by the droplet growth, which is driven by the remaining sub-cooling.

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Nomenclature

c_p [J kg^{-1}K^{-1}]	specific heat capacity at constant pressure
e [J m^{-3}]	total energy
γ [−]	specific heat ratio
χ [−]	wetness (mass fraction of liquid phase)
J [m^{-3} s^{-1}]	nucleation rate
$k_B = 1.3804 \cdot 10^{-23}$ J K^{-1}	Boltzmann constant
Kn [−]	Knudsen number
L [J kg^{-1}]	latent heat of evaporation/condensation
λ [W m^{-1} K^{-1}]	thermal conductivity
$m_1 = 2.99046 \cdot 10^{-26}$ kg	mass of one molecule of water
μ [Pa s]	dynamic viscosity
p [Pa]	pressure
r [m]	droplet radius
R [J kg^{-1} K^{-1}]	gas constant
ρ [kg m^{-3}]	density
s [J kg^{-1} K^{-1}]	entropy
σ_∞ [N m^{-1}]	surface tension
t [s]	time
T [K]	temperature
u, v [m s^{-1}]	velocity components
x, y [m]	spatial coordinates

Subscripts

0	total (reservoir)
c	critical
ℓ	liquid
s	saturated
v	vapor

The flow downstream nucleation start is two-phase flow of gas with dispersed liquid phase in form of droplets. Most general models are based on the two-fluid models with separate set of equations for each phase, see e.g. [5,26] or [30]. If we omit film condensation and coarse water effects, then droplets created by nucleation usually have sub-micron diameter and therefore there is almost zero slip velocity between droplets and gas and it is quite common practice to consider the single-fluid model, i.e. the model with the same velocity field for both vapor and condensed droplets, see e.g. [6,9,31] or [1]. Another issue is modeling of droplet size spectra, where simple models are based on the single average size of droplets, e.g. [1], more general models use the method of moments, see e.g. [14] or [25], or the quadrature method of moments, see e.g. [17].

Now consider the non-equilibrium condensation in a nozzle, which is characterized by rising vapor sub-cooling until the start of nucleation (Wilson point), intensive sub-cooling drop due to nucleation and following droplet growth. The liquid mass fraction (wetness) in such case is equal to zero until the nucleation start and it approaches the equilibrium wetness in the region of droplet growth. This behavior motivated us to test an approximate model of non-equilibrium condensation based on the "switch", which changes the wetness from zero to the equilibrium value at the approximate location of Wilson point. This model has of course some limitations and it is intended rather for simplified simulations during early steps of turbine design. This approximate model has been already tested with success for the 1D and 2D flow in an axisymmetric nozzle for apriori set wetness in Wilson point, see [11]. Here we present the extension of this model with a local setting of Wilson point according to expansion rate. Numerical results for nozzle and turbine cascade flows achieved by this simplified model are compared to the results achieved by the method, which we call typical.

The typical method is based on the solution of the fully Eulerian single-fluid model with the droplet size spectrum approximated by the method of moments [14]. The thermodynamic properties of steam are modeled using the real gas model of IAPWS-95 for metastable region [23] or the perfect gas mode, which can be used for low pressures.

2. Typical flow model

The method, which we call "typical" is based on the solution of single fluid model. It consists of the set of partial differentialen equations

$$\frac{\partial W}{\partial t} + \frac{\partial F}{\partial x} + \frac{\partial G}{\partial y} = P \tag{1}$$

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