21st International Conference **ENGINEERING MECHANICS 2015**
Svratka, Czech Republic, May 11 –14, 2015
Paper **#012, pp. 104–105**

Numerical Solution of Wet Steam Flow through Blade Stage

Vladimír Hric[1,a], Jan Halama[2,b]

[1]Dpt. of Technical Mathematics, FME CTU, Karl. nám. 13, CZ-12135 Prague 2, Czech Republic

[2]Institute of Thermomechanics, AS CR, Dolejškova 5, CZ-18200, Prague 8, Czech Republic

[a]vladimir.hric@fs.cvut.cz, [b]jan.halama@fs.cvut.cz

Keywords: wet steam, nucleation, two-phase, blade

Abstract: We present in a rather simple way an engineering approach to numerical modeling of transonic flow of wet steam through the blade-to-blade channel. Due to the non-equilibrium vapor-to-liquid phase transfer process additional transport equations must be append to the traditional system of equations which describes fluid flow. We limit our flow model to the laminar case (compressible Navier-Stokes equations). Further, we assume zero difference in velocities of vapor and liquid phase (no-slip condition), low mass fraction of liquid phase (less than 8 per-cent) and homogeneous dispersion of droplets in vapor steam. Obtained results are in satisfactory accordance with experimental measurements.

Introduction

When the expansion of a condensable fluid (e.g. dry steam) is rapid and the expansion curve cross the equilibrium saturation, initially superheated steam remains dry until certain supersaturation (or supercooling) is attained. Therefore, naive equilibrium modeling of flow field parameters cannot be used. In the wet region as the expansion and supercooling proceed, critical clusters of molecules of liquid water are continuously created, but these clusters can further grow to the water droplets only if critical work of formation of the second phase is exceeded (otherwise clusters decay). This occurs at the region of maximum supercooling (so-called Wilson region). In the steam turbines condensation occurs in the last stages. Presence of water droplets results in the additional losses and are the cause of blade erosion. Hence, reliable and accurate CFD simulations can be interesting for turbines' manufacturers.

Flow model

Following hyperbolic system of partial differential equations is numerically solved

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

Vectors W, F, G, P, R, S have eight componenents (in 2D) and take the form

$$\begin{aligned}
&W=\{\rho,\rho u,\rho v,\rho E,\rho Q_0,\rho Q_1,\rho Q_2,\rho y\}^T\\
&F=\{\rho u,\rho vu,\rho u^2+p,\rho Eu+pu,\rho Q_0 u,\rho Q_1 u,\rho Q_2 u,\rho yu\}^T\\
&G=\{\rho v,\rho uv,\rho v^2+p,\rho Ev+pv,\rho Q_0 v,\rho Q_1 v,\rho Q_2 v,\rho yv\}^T\\
&P=\left\{0,\tau_{xx},\tau_{xy},u\tau_{xx}+v\tau_{xy}+\lambda\tfrac{\partial T}{\partial x},0,0,0,0\right\}^T\\
&R=\left\{0,\tau_{xy},\tau_{yy},u\tau_{xy}+v\tau_{yy}+\lambda\tfrac{\partial T}{\partial y},0,0,0,0\right\}^T\\
&S_n=\{0,0,0,0,J,r_cJ,r_c^2J,4\pi\rho_\ell r_c^3J/3\}\\
&S_g=\{0,0,0,0,0,\ \ldots\\
&\qquad\ldots\ \rho\left(aQ_{-1}+bQ_0+cQ_1\right),2\rho\left(aQ_0+bQ_1+cQ_2\right),4\pi\rho_\ell\rho\left(aQ_1+bQ_2\right)+3c\rho y\}
\end{aligned} \tag{2}$$

where W is vector of conserved variables, F and G are vectors of inviscid fluxes, P and R are vectors of viscous fluxes, S_n is liquid mass source due to nucleation, S_g is liquid mass source due to growth of droplets, ρ is density of the whole mixture, u and v are components of velocity vector, E is total energy of mixture and consists of internal energy of vapor phase, internal energy of liquid phase, energy stored in the phase interface and kinetic energy of mixture, p is static pressure, Q_i is i-th moment of droplet number distribution function, y is wetness, τ_{ij} are components of shear stress tensor, λ is coefficient of thermal conductivity of vapor phase and T is absolute temperature. This system of equation is solved by the cell-centered finite volume discretisation process with inviscid flux scheme of AUSM type. Symmetrical splitting of Strang is employed in order to resolve stiff character of the system. Closure of the system comprises of equation of state for vapor phase suitable for CFD purposes [6], simple relations for saturated liquid parameters, relation for nucleation rate J [3] and droplet growth model in the form $g(r) = a/r + b + cr$ [5, 4].

Basic results and conclusion

We validate the above mentioned flow model on the flow through Bakhtar cascade [1, 2]. Presented flow model gives slightly shifted zone of nucleation onset comparing to the experimental results. Distribution of wetness and droplet size are in good accordance with other researchers.

Acknowledgments: The support of the grant GA ČR 101/11/1593 and the grant
No. SGS13/174/OHK2/3T/12 of CTU in Prague is gratefully acknowledged.

References

[1] F. Bakhtar, M. Ebrahimi, R.A. Webb: On the Performance of a Cascade of Turbine Rotor Tip Section Blading in Nucleating Steam, part 1, Surface Pressure Distributions, IMechE Proc Instn Mech Engrs 209 (1995) 115–124.

[2] F. Bakhtar, M. Ebrahimi, B.O. Bamkole: On the Performance of a Cascade of Turbine Rotor Tip Section Blading in Nucleating Steam, part 2, Wake Traverses, IMechE Proc Instn Mech Engrs 209 (1995) 169–177.

[3] F. Bakhtar, J.B. Young, A.J. White, D.A. Simpson: Classical Nucleation Theory and Its Application to Condensing Steam Flow Calculations, Proc IMechE 219(C) (2005) 1315–1333.

[4] A.J. White: A Comparison of Modelling Methods for Polydispersed Wet-Steam Flow, Int J Numer Meth Engng 57 (2003) 819–834. 1

[5] M.J. Moore, C.H. Sieverding: Two-Phase Steam Flow in Turbines and Separators, Hemisphere Publishing Corp. (1976).

[6] J. Hrubý, J. Pátek, M. Duška, An Analytical Formulation of Thermodynamic Properties of Dry and Metastable Steam Suitable for Computational Fluid Dynamics Modelling of Steam Turbine Flows, J Power and Energy 228 (2014) 120–128.