ZÁPADOČESKÁ UNIVERZITA V PLZNI

FAKULTA STROJNÍ

KATEDRA ENERGETICKÝCH STROJŮ A ZAŘÍZENÍ

ZÁPADOČESKÁ UNIVERZITA V PLZNI

POWER SYSTEM ENGINEERING, THERMODYNAMICS & FLUID FLOW

2012

JEDNOTLIVÝ PŘÍSPĚVEK ZE SBORNÍKU

evropský sociální fond v ČR

EVROPSKÁ UNIE

MINISTERSTVO ŠKOLSTVÍ, MLÁDEŽE A TĚLOVÝCHOVY

OP Vzdělávání pro konkurenceschopnost

INVESTICE DO ROZVOJE VZDĚLÁVÁNÍ

ASSESSMENT OF THE WETNESS ENERGY LOSS IN 1000 MW NUCLEAR AND 210 MW FOSSIL LP STEAM TURBINES

PETR Vaclav, KOLOVRATNIK Michal

This paper presents results of computational analysis of the wet steam energy loss occurring in 1000 MW nuclear and 210 fossil MW LP steam turbines. The turbines operate under considerably different conditions as regards pressure level in the droplet nucleation zone, exit moisture level and droplet size spectra determined from the optical extinction measurements. The evaluation of the basic wetness energy losses was carried out covering thermodynamic loss, drag loss of the fine and coarse droplets, impact loss, collected water loss, centrifuging loss and exit loss. Statistical 2D evaluation method was employed throughout the computational simulation of the loss.

Keywords: steam turbine, wet steam, wetness energy loss

Introduction

Continuously increasing demand for power has supported many investigations of the wetness effects both in the fossil and nuclear steam turbines. The extensive and fruitful review of the state of the subject was recently presented in Special Issue on Wet Steam [1]. A number of review articles summarize here the state of progress in theoretical and experimental studies associated with wetness effects in steam turbines.

Existing current knowledge and mathematical models on wet steam flow in steam turbines can now be used with acceptable approximation for detailed CFD evaluation of the droplet nucleation and prediction of the wet steam energy losses. Thus, it can be used in aerodynamic optimization of the turbine nozzle and rotor blade rows operating under wet steam conditions. This paper is aimed at presenting results of computation of the wetness loss in the 1000 MW nuclear and 210 MW fossil LP steam turbines. The computational analysis accounts for the basic wetness energy losses covering thermodynamic loss, drag loss of the fine and coarse droplets, impact loss, collected water loss, centrifuging loss and exit loss. The analysis in principal follows the method developed in [2] and [3]. Statistical 2D evaluation method ([4], [5], [6]) was employed throughout the computational simulation of the losses. It consists in a random character of dissipation undertaken by a fluid particle passing through the multi-stage LP steam turbine. Different particles thus undergo different nucleation conditions resulting in a broader distribution of the droplets sizes.

1. Operating conditions and experimental data employed in the analysis of the wetness loss

The analysis of the wetness energy losses concerns the conditions in the 1000 MW nuclear and 210 fossil LP steam turbines. Principal design arrangement is seen in Fig. 1 and Fig. 2 and the base load operating conditions in Tab. 1.

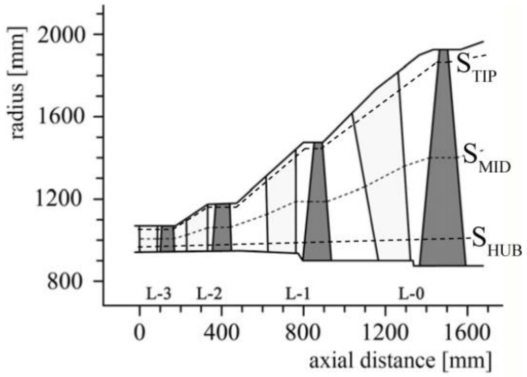

Fig. 1: Meridional cross-section of the 4-stage 1000 MW LP turbine

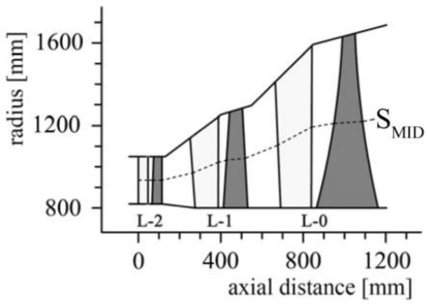

Fig. 2: Meridional cross-section of the 3-stage 210 MW LP turbine

			1000 MW nuclear	210 MW fossil
L-0 rotor blade length	l	[mm]	1085	840
LP inlet parameters	p_{IN}	[kPa]	772	131
	T_{IN}	[˚C]	250	181
LP exhaust pressure	p_{ex}	[kPa]	7.4	4.9
Turbine output		[MW]	1004	200
Mean pressure and expansion rate in the Wilson zone	p_W	[kPa]	122.1	22.8
	P_W	[s^{-1}]	1330	1440
Design steam mass flow in L-0 stage		[$kg\cdot s^{-1}$]	144.5	54.5

Table 1: Base load operating conditions of the 1000 MW nuclear and 210 MW fossil LP steam turbines

Measurements with the optical extinction probe [7], [8] carried out downstream from the final stage of the considered turbines give distribution of the steam wetness introduced in Fig. 3.

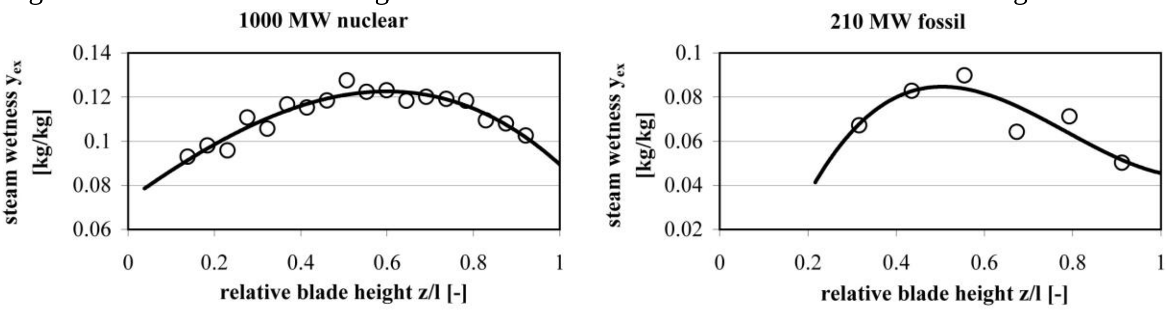

Fig. 3: Wetness distribution measured downstream from the final stage

In addition, a considerable difference in Sauter mean diameter of fine droplets in the considered LP steam turbines can be seen in the Tab. 2. These important experimental information were used in the following numerical simulation of the droplet nucleation process and the wet steam energy losses.

	1000 MW nuclear	**210 MW fossil**
D_{32} [μm]	0.464	0.123
N [kg^{-1}]	$5.25\cdot10^{15}$	$1.26\cdot10^{17}$
y [$kg\cdot kg^{-1}$]	0.121	0.0779

Table 2: Results of the extinction measurement at the exit of L-0 turbine stages – blade mid-height

2. Wet steam energy loss

In principal, the evaluation of the losses follows the method developed by Gyarmathy [2] with some additional corrections. It concerns mainly the acceleration of the coarse droplets with variable relative velocity in between the stator and rotor blades, deposition of the fine droplets by turbulent diffusion [9] and, the effect of deposited moisture on the exit energy loss. Similar approach was presented in [3].

The following wetness energy loss sources are considered:

- Δq_1 - thermodynamic loss (due to mass and heat transfer between liquid and vapour phases including nucleation process in the Wilson zone)
- Δq_2 - drag loss of fine droplets (work of frictional force due to relative velocity between the fine droplets and vapour)
- Δq_3 - drag loss of coarse droplets (energy needed to accelerate coarse droplets in between the stator and rotor blades)
- Δq_4 - impact loss (resistant effect on the rotor blades of the coarse droplets due to different inlet velocity triangle from the steam velocity triangle)
- Δq_5 - collected water loss (deposited water on the rotor blades is centrifuged to the outer casing without producing useful work in the current and followings downstream stages)
- Δq_6 - centrifuging loss (energy needed to centrifuge collected water on the rotor blades out to the tip of the blades due to the change in rotational velocity)
- Δq_7 - exit energy loss (difference of the equilibrium and nonequilibrium kinetic energy of the wet steam flow at the exit of L-0 turbine stage accounting for subcooling and deposited moisture)

As regards to the thermodynamic loss Δq_1 and drag loss Δq_2, the principal of entropy production along the streamlines is used within the blade passage followed by a relaxation region past the blade row [10].

The droplet nucleation model based on the corrected classical nucleation theory (CNT) employed in the computational simulation of the wet steam energy losses is introduced in Appendix 1.

Statistical 2D evaluation method was employed throughout the computational simulation of the losses Δq_1- Δq_7 in the considered multistage LP steam turbines. The method accounts for the wake chopping effect on droplet sizes [4]. It is based on a random character of dissipation undertaken by fluid particle passing through the multistage turbine, depending on its randomly chosen streamline (2D approach) within each blade row with a given pitch-wise distribution of polytropic efficiency. Different fluid particles, thus, undergo different nucleation conditions resulting in a broader distribution of droplet sizes. At least 10^4 steam particles had to be launched at the LP turbine inlet to obtain statistically valid result at the turbine outlet. The method was used with promising results in preceding papers [6], [11].

Resulting wetness energy losses generating at the blade mid-height for each stage of the considered nuclear and fossil LP steam turbines are introduced in Fig. 4.

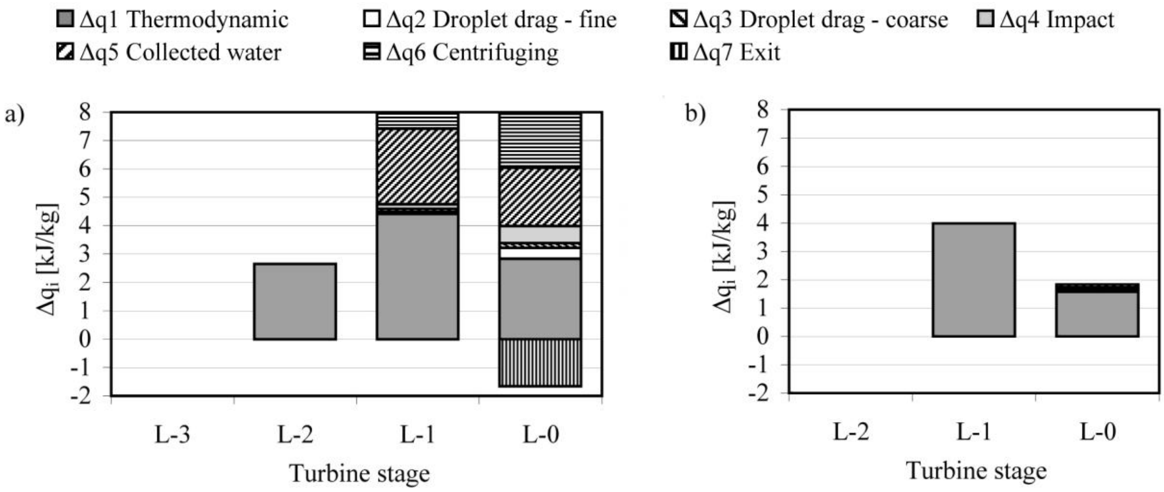

Fig. 4: Wetness energy losses a) 1000 MW nuclear LP steam turbine
b) 210 MW fossil LP steam turbine

As it is seen in Fig. 4, there is a considerable difference in the wetness loss in the considered nuclear and fossil LP steam turbines. This is mainly consequence of difference in the droplet size spectra which are responsible for more than one order smaller turbulent diffusion and impact deposition coefficients in the fossil turbine. It thus resulted in negligible energy losses Δq_2 - Δq_7 and dominating thermodynamic loss Δq_1. It is seen further that the thermodynamic loss occurs not only in the nucleating stage, but attains comparable values in the next stages too. It is mainly a consequence of the used statistical computation method in 2D approach, thus accounting for increased subcooling near the suction side of the blades [6].

Different operating conditions (Tab. 1) of the considered nuclear and fossil LP steam turbines thus resulted in almost 2.5-times lower total absolute wetness loss in the fossil LP steam turbine. This positive effect arises mainly from the lower mean pressure level in the nucleation Wilson zone what resulted in smaller mean Sauter diameter D_{32} as it can be seen in Tab. 2.

3. Wet steam energy loss along the blade height of the 1000 MW nuclear LP steam turbine

Different flow conditions in the hub-, mid- and tip- regions of the bladed flow path, would be evidently responsible also for different wet steam losses. To account for these flow differences (at least approximately), the following evaluation of the losses was carried out on the stream surfaces S_{HUB}, S_{MID} and S_{TIP} (Fig. 1).

The unknown mean polytropic efficiencies within the bladed flow path on the stream surfaces S_{HUB}, S_{MID} and S_{TIP} were predicted in the matching computational process. It consisted in fitting computed steam wetness to the corresponding measured value (Fig. 3) downstream of the final stage by means of varying the unknown polytropic efficiency.

Resulting total separate wetness energy losses generating on the considered stream surfaces S_{HUB}, S_{MID} and S_{TIP} (Fig. 1) are depicted in Fig. 5.

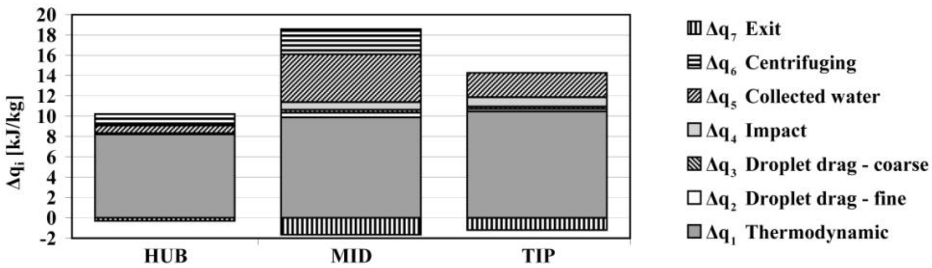

Fig. 5: Distribution of the total wetness energy losses (1000 MW nuclear LP)

In addition, a distribution of the current wetness energy losses generating in the corresponding blade rows is seen in Fig. 6 to enable better analysis of the results (N-nozzle blade row, R-rotor blade row).

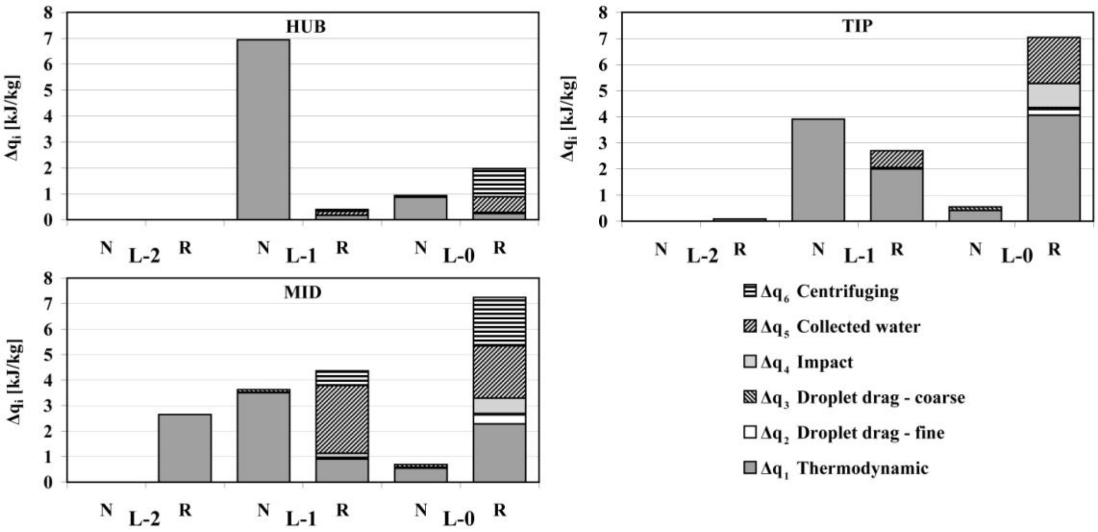

Fig. 6: Distribution of the current wetness energy losses in the blade rows of the 1000 MW nuclear LP steam turbine

Referring to the results introduced in Fig. 6 it is possible to give the following comments:

i) Along the hub-stream surface S_{HUB} the droplet nucleation occurs at high expansion rate of order P = 3100 s^{-1} within the nozzle blade rows of the turbine stage L-1. It results in pronounced thermodynamics loss Δq_1 and small droplet size of order D_{32} = 0.2 μm at the turbine exit. It considerably supress subcooling of steam and Δq_1 in the following downstream blade rows. It also means small deposition of the fine droplets on the blade surfaces. As a consequence, low wet steam losses depending on deposited water can be observed.

ii) Rather different conditions prevail on the mid-stream surface S_{MID}. Droplet nucleation is occurring here in the rotor blade rows of the L-2 turbine stage at expansion rate of order P = 750 s^{-1} and 1000 s^{-1} in the following nozzle blade rows of the L-1 turbine stage. As a result, the large droplets are formed of order D_{32} = 0.7 μm at the turbine exit. It implies considerable deposition of the fine droplets and increased value of the other wet steam losses. In addition, secondary thermodynamic loss Δq_1 can be observed also in the rotor blade rows of the last turbine stage L-0.

iii) Similar development (as on the S_{MID}) of the losses can be observed on the tip-stream surface S_{TIP}. The expansion rate within nucleation region is of order P = 700 s^{-1} what gives large droplets of order D_{32} = 0.72 μm at the turbine exit. It thus implies similar consequences as on the mid-stream surface.

Preceding discussion suggests in principal that the size of droplets and steam wetness are supposed to be the most important parameters affecting the wet steam energy losses. It affects considerably not only the thermodynamic loss Δq_1 but all other losses too ($\Delta q_2 - \Delta q_7$), through deposited fine droplets on the blade surfaces. On the other side, these parameters depend on the LP turbine steam inlet conditions (p_{IN}, T_{IN}), exhaust pressure (p_{ex}) and design details of the bladed flow path.

Conclusions

The corrected classical nucleation theory (CNT) of pure steam (in Apendix 1) was found to be an adequate nucleation model for predicting droplet nucleation in LP steam turbines. It was applied to the 1000 MW nuclear and 210 MW fossil LP steam turbines with considerably different operating conditions as regards to pressure level in the nucleation Wilson zone. The statistical computation method provided droplet size spectra which are in a good agreement with results obtained by means of optical extinction measurements carried out down stream from the final stage of the considered LP steam turbines.

Resulting considerably different droplet size spectra, properly described by the corrected CNT, provided also considerably different wetness loss in the nuclear and fossil LP steam turbines. The size of droplets and steam wetness were found to be the most important parameters affecting the wet steam energy losses.

It can, thus, be concluded that the corrected CNT of pure steam can serve, so far, as an adequate model for engineering prediction and analysis of the wet steam effects in the LP steam turbines.

Further approach to the real physical picture of the droplet nucleation in the LP steam turbines can be expected from continuing experimental research, aimed at a better understanding of the real nature of chemical impurities (molecular, ionic, hydrated), together with the development of related multicomponent droplet nucleation models.

Literature

[1] Bakhtar, F., (Guest Editorial), 2005a. Special Issue on Wet Steam, Part 1, 2. Proc. Inst. Mech. Engrs., Vol. 219, Part C.

[2] Gyarmathy, G., 1962. Grundlagen einer Theorie der Nassdampfturbine. Diss. ETH Zűrich. Zűrich, “Juris”.

[3] Laali, A. R., 1991. A new approach for assessment of the wetness losses in steam turbines. From authors.

[4] Bakhtar, F. and Heaton, A. V., 2005b. Effects of wake chopping on droplet sizes in steam turbines. Proc. IMechE Vol. 219 No C12: J. Mechanical Engineering Science, Special Issue on Wet Steam – Part 2, 1315-1333.

[5] Guha, A. and Young, J., 1994. The Effect of Flow Unsteadiness on Homogeneous Nucleation of Water Droplets in Steam Turbines. Phil. Trans. Roy. Soc., Series A, 349:445-472.

[6] Petr, V. and Kolovratnik, M., 1999. Modelling of the Droplet Size Distribution in LP Steam Turbine. 3rd European Conference on Turbomachinery, Fluid Dynamics and Thermodynamics. Inst. Mech. Engrs. Conference Transections 1999-1B, London, 771-782.

[7] Petr, V. and Kolovratnik, M., 2003a. Diagnostics of Wet Steam in LP Steam Turbines. 5th European Conference on Turbomachinery, Fluid Dynamics and Thermodynamics, Prague, 687-698.

[8] Petr, V., Kolovratnik, M. and Hanzal, V., 2003b. Instrumentation and Tests on Droplets Nucleation in LP Steam Turbines. Power Plant Chemistry, No. 7, 5:389-395.

[9] Yau, K. K. and Young, J. B., 1987. The Deposition of Fog Droplets on Steam Turbine Blades by Turbulent Diffusion. ASME Journal of Turbomachinery, July, 109:429-435.

[10] Petr, V., 1987. A Survey of Relaxation Losses in a Turbine Blading Operating in Wet Steam. Proceedings IMechE Conference C265/87: Turbomachinery-Efficiency Prediction and Improvement, 113-119.

[11] Petr, V. and Kolovratnik, M., 2011. Classical Nucleation Theory as an Adequate Model in Predicting Related Wet Steam Effects in LP Steam Turbines. 9th European Conference on Turbomachinery, Fluid Dynamics and Thermodynamics, Istanbul, 991-1003.

[12] Bakhtar, F., Young, J. B., White, A. J. and Simpson, D. A., 2005c. Classical nucleation theory and its application to condensing steam flow calculations. Proc. IMechE Vol. 219 No C12: J. Mechanical Engineering Science, Special Issue on Wet Steam - Part 2, 1357-1367.

[13] Deitch, M.Je. and Filippov, G.A., (1981). *Fluid Dynamics of Two-Phase Flows.* Energoizdat, Moscow.

[14] Moore, M. J., 1976. Gas Dynamics of Wet Steam and Energy Losses in Wet-Steam Turbines. In Two-Phase Steam Flow in Turbines and Separators (Eds. M. J. Moore and C. H. Sieverding), 1976, Chapter 2. Washington, "Hemisphere".

Acknowledgment

This work has been supported by Grant No. 101/11/1593 of the Grant Agency of the Czech Republic.

Appendix 1: Droplet nucleation model

Discussion introduced in [11] suggests that the corrected classical nucleation model (CNT) can serve, so far, as an adequate model for engineering prediction and analysis of the wet steam effects in LP steam turbines. It is summarized as follows.

Assessment of the complete droplet nucleation process of impure steam, occurring in the LP steam turbine flow path, is still far from the final solution. It is mainly because of the unknown state of impurities (molecular, hydrated or ionic) which determines the nucleation model and provides needed input data in the multicomponent nucleation models. In fact, there is no general agreement for the nucleation model even for pure steam, as it is shown by Bakhtar et al. [12].

With regard to the mentioned uncertainties the classical nucleation model (CNT) applied to unary homogenous nucleation of pure steam is employed in the analysis. The critical radius of droplets and the nucleation rate [1/m^{3}s] is then evaluated according to classical Becker and Dörring theory, i. e. [12]

$$r_c = \frac{2 \cdot \sigma_\infty}{\rho_l \cdot R \cdot T_v \cdot \ln\left[p / p_s(T_v)\right]} \tag{A1.1}$$

$$J = \sqrt{\frac{2 \cdot \sigma_\infty}{\pi \cdot m^3}} \cdot \frac{\rho_v^2}{\rho_l} \cdot \exp\left(-\beta \cdot \frac{4 \cdot \pi \cdot r_c^2 \cdot \sigma_\infty}{3 \cdot k_B \cdot T_v}\right) \tag{A1.2}$$

Introduced correction factor β in the exponential term of eq. (A1.2), accounts for existing uncertainties in the nucleation model, can be assumed as [13]

$$\beta = a \cdot (p_{os})^{b} \tag{A1.3}$$

In eq. (A1.3) p_{os} [bar] means the pressure at the intersection of expansion and steam saturation lines. The adjustable coefficients a, b are to be determined according to measurements. Comparison of the measured and evaluated light transmittance data in the considered LP steam turbines have suggested the values [11]

$$a = 1.16 \tag{A1.4a}$$
$$b = 0.20 \tag{A1.4b}$$

The pressure level for applying eqs. (A1.4a), (A1.4b) into the eq. (A1.3) covers the range p_{os} = (0.15÷2) bar, which satisfies the LP steam turbine operating conditions.

The flat surface tension σ_∞ of a nucleus in eqs. (A1.1) and (A1.2) is evaluated according to IAPWS release (1994) on surface tension of ordinary water substance,

$$\sigma_\infty = 0.2358 \cdot \tau^{1.256} \cdot (1 - 0.625 \cdot \tau) \tag{A1.5}$$

$$\tau = 1 - T/T_c \;, T_c = 647.096\,\mathrm{K}\,,\; T < T_c$$

In the present analysis the droplet growth rate equation formulated in [2] is employed during the condensation process i. e.

$$\frac{dr_d}{dt} = \frac{1}{h_{lv} \cdot \rho_l} \cdot \frac{\lambda_v}{r_d} \cdot \frac{1}{1 + 3.18 \cdot Kn} \cdot \Delta T \cdot \left(1 - \frac{r_c}{r_d}\right) \tag{A1.6}$$

The nucleation and condensation process occurring in the multistage LP steam turbine flow path is then evaluated with use of standard system of governing equations for condensing steam flow (e.g. [2], [14]) together with the real thermodynamic steam properties.

Prof. Ing. Vaclav PETR, DrSc., CTU in Prague, Technicka 4, 166 07 Prague 6, CZ,
vaclav.petr@fs.cvut.cz
Doc. Ing. Michal KOLOVRATNIK, CSc., CTU in Prague, Technicka 4, 166 07 Prague 6, CZ,
michal.kolovratnik@fs.cvut.cz