CONDENSATION OF STEAM WITH CHEMICAL IMPURITY IN A TURBINE

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ABSTRACT

The approach used in the paper for the condensation of flowing steam is based on the binary nucleation of water and a representative chemical impurity NaCl. The physical and mathematical models are briefly described. The binary nucleation numerical model is tested on steam flow with condensation in a Laval nozzle with a low expansion rate of about $P_r = 1000\ \mathrm{s}^{-1}$ in the divergent part of the nozzle. The calculated results for the pressure distribution are compared with experiments. The binary nucleation numerical model is used for the calculation of steam flow with condensation in the 2D nozzle-blade cascade of the first wet stage of the low-pressure (LP) part of a condensing steam turbine. Calculations of the flow in the cascade at high and low expansion rates are presented.

NOMENCLATURE

a		Activity coefficient for water and chemical impurity
M		Mach number
P, p	Pa	Pressure
P_r	s^{-1}	Expansion rate, $P_r = -(w/p)\,dp/ds$
Q_0	kg^{-1}	Number of droplets per unit mass of steam
Q_2	$\mathrm{m}^2\,\mathrm{kg}^{-1}$	Sum of droplet radii squared per unit mass of steam
r	m	Droplet radius
R_2	m	Surface-area averaged droplet radius, $R_2 = (Q_2 / Q_0)^{0.5}$
s	m	Length
T	K	Temperature
ΔT, ΔT_{NaCl}	K	Subcooling, $\Delta T = T_S - T$, $\Delta T_{NaCl} = T_{TPB} - T$
w	$\mathrm{m\,s}^{-1}$	Velocity
y	%	Wetness
σ_p	$\mathrm{N\,m}^{-1}$	Flat surface tension

Subscripts

at	Total inlet
e	Outlet
is	Isentropic
max	Maximum
p	Heterogeneous, with chemical impurity
s	Saturation
TH	Throat
1	Steam

Acronyms

LP	Low pressure
SSL	Steam saturation line
SSZ	Salt solution zone
TPB	Three-phase boundary

1 INTRODUCTION

The flow of steam with nucleation and condensation in steam turbines is still an open problem. This is mainly due to the effects of chemical impurities contained in the steam. The effects of chemical impurities on nucleation and the subsequent condensation occur mainly in the salt solution zone (SSZ). The approach used in this paper is based on the binary nucleation of a chemical impurity NaCl and water. Physical and mathematical models are mentioned and tested on steam flow with condensation in a Laval nozzle with a low expansion rate of about $P_r = 1000\ \mathrm{s}^{-1}$ in the divergent part of the nozzle.

The mathematical model and code for the binary nucleation of NaCl and water are also applied to the nozzle cascade of the first wet stage of the LP part of a 200 MW condensing steam turbine. These calculations help in clarifying the different structures related to steam flow with heterogeneous condensation and high and low expansion rates.

2 STEAM EXPANSION IN THE PHASE TRANSITION ZONE

The real steam expansion lines based on measurements in phase transition zone of 200 MW steam turbine are evident in enthalpy-entropy h-s diagram - see Fig. 1.

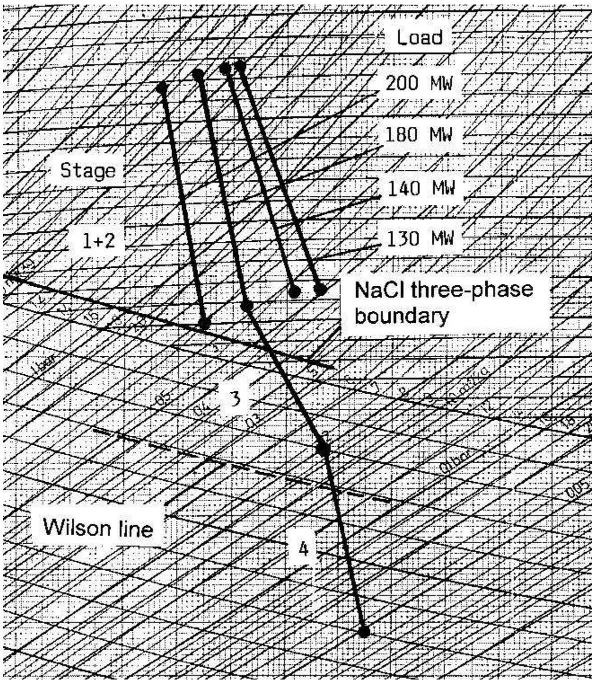

Fig. 1: h-s diagram of steam expansion in 200 MW turbine LP part

It is visible in h-s diagram that the steam expansion line intersects (NaCl) three-phase boundary (TPB) that is the solution saturation line, further passes through the salt solution zone (SSZ) that is the zone between solution saturation and steam saturation lines and intersects the steam saturation line (SSL). All these effects appear in the third (L-1) stage. Expansion in L-1 stage shows an important increase of entropy as the consequence of thermodynamic loss and subcooling of the steam.

The Wilson line for spontaneous condensation is also drawn in the h-s diagram. It is based on Gyarmathy and Meyer (1965) measurements that were performed for the expansion rate in the interval $P_r = 1\text{-}5 \cdot 10^3$. The corresponding equilibrium wetness at the Wilson line amounts y = 3.1 ± 0.2 %. It follows that the phase transition zone, from the top at TPB down to Wilson line, is here situated in the L-1 stage and partly in the fourth last stage.

The expansion of subcooled steam under SSL is connected with a thermodynamic loss. In the case of pure water steam expansion from saturation pressure $P_s = 50{,}000$ Pa, the subcooling and the thermodynamic loss will be like in Tab. 1 (see the Baumann rule).

Pressure ratio P/P_s:	1.0	0.8	0.6	0.5	0.4
Subcooling °C:	0.0	12.33	27.19	36.04	46.30
Thermodynamic loss %:	0.0	1.23	2.78	3.73	4.87
Outlet wettnes (is) %:	0.0	1.1	2.6	3.4	4.4

Tab. 1: Isentropic expansion of pure water steam under SSL ($P_s = 50{,}000$ Pa)

Nucleation of two types can occur in the steam flowing in a nozzle or in a turbine: spontaneous (homogeneous) and heterogeneous. Spontaneous nucleation occurs during the expansion of pure steam below the steam saturation line (SSL) at sufficient subcooling. This is followed by the growth of the droplets due to condensation. Heterogeneous or binary nucleation can start in the salt solution zone (SSZ) which is above the SSL by nucleation on chemical impurities contained in the superheated steam.

Superheated steam, expanding through a steam turbine contains impurities of various kinds. From the point view of heterogeneous nucleation, it is possible to divide these impurities into two categories. Solid particles, insoluble in water and in the steam, fall into the first category. The concentration of these solid impurities in the steam is most probably too small to affect the nucleation process to any significant degree.

Chemicals that are soluble in steam form the second category. These chemicals can be dissolved in superheated steam and they can also be present in the form of molecular clusters. There are numerous inorganic and organic chemicals in the second category. The impurities in the superheated steam inside a steam turbine are mainly (Bellows, 1999) NaCl, Na_2SO_4, sodium acetate, etc. In what follows, we shall focus on NaCl, a chemical that is most often present in the steam and the properties of which are well-researched.

3 COMPUTATIONAL MODEL

The two-dimensional wet steam flow is described by the system of Euler equations. The system is linked with equations describing binary nucleation and with equations describing water droplet growth by condensation. The NaCl impurity is assumed to be in nucleus form, its mass is neglected and the concentration is sufficiently high.

The mathematical model of binary nucleation is based on the Becker and Doering (1935) relationship for the nucleation rate for pure steam. The Becker-Doering theoretical formula is corrected by empirical parameters. Values of these parameters were obtained by fitting to experimental results obtained with pure steam in a shock tube (Lankaš, 1997).

In contrast to the spontaneous nucleation of pure steam, some changes have been carried out in the relationships for binary nucleation. The supersaturation S is defined by,

$$S = \frac{p_1}{p_{sp} a_p} \tag{1}$$

where p_{sp} is the saturation pressure at the TPB and $a_p = 0.71668$ is the activity coefficient for water and NaCl. The flat surface tension σ_p is defined for a saturated water solution of NaCl in the embryo and is described by an empirical function of temperature T. Data for a_p and σ_p

were used on the basis of the publication by Gorbunov and Hamilton (1997). For the saturation pressure p_{sp} at the TPB and low pressures (0.5-2.0 bar) an empirical function of temperature T was created by Šťastný and Šejna (2012).

The system is linked with equations describing the growth of heterogeneous droplets by water vapour condensation starting from the critical radius of the droplets. The relation of Gyarmathy (1963) is used.

It is assumed that the model will be used only for small total wetness ($y < 5.0$ %), and that the vapour phase can be considered as an ideal gas at low pressures. It is also assumed that there is no slip between the vapour phase and the droplets.

The finite-volume method is used for the solution of the system of equations for binary condensation. The 2D domain is discretized by an unstructured triangular mesh. This mesh is locally refined, especially in the area of the nucleation zone. The number of triangles ranges from 10,000 to 100,000. A hybrid explicit TVD/up-wind scheme is used to solve the problem numerically.

4 APPLICATIONS OF THE COMPUTATIONAL MODEL

The binary nucleation numerical model was applied for the calculation of the flow with condensation in an experimentally tested nozzle and in a turbine cascade.

The nucleation of steam on the NaCl nuclei under the TPB is still an open problem. The concentration of the nuclei depends first of all on the mass concentration of NaCl in the superheated steam. The guideline mass concentration values for the steam entering a steam turbine are usually taken as: Na < 5 μg/kg steam, Cl < 3 μg/kg steam and NaCl < 5 μg/kg steam. The concentration of nuclei is then high enough to produce extensive binary nucleation under the TPB. This is the main assumption of the computational model. It should be noted that a NaCl mass concentration of 1 μg/kg steam is equal to a molecular concentration of 1.03×10^{16} molecules/kg steam.

4.1 2D Nozzle and Flow Mode

A nozzle with a low expansion rate in the divergent part of the nozzle of about $P_r = 1000\ \mathrm{s}^{-1}$ was used for testing the computational model - see Šťastný and Šejna (2008). The same nozzle was used in experiments performed at the Czech Technical University (CTU) by Petr and Kolovratník (1999). The selected total inlet parameters are: $P_{at} = 250{,}000$ Pa, $T_{at} = 418.15$ K. It then follows that the inlet superheat is $(T_{at} - T_s) = 17.6$ K. The flow in the nozzle is transonic and steam condensation occurs.

The CTU experimental facility was supplied with steam from two oil-fired boilers. The impurity levels of the steam were: Na < 25 μg/kg steam, Cl < 25 μg/kg steam, $S0_4$ < 15 μg/kg steam, PO_4 < 10 μg/kg steam, dissolved organics (DO) < 30 μg/kg steam (Petr and Kolovratník, 1999).

4.2 Results for the Nozzle

The calculated variation of relative pressure P/P_{TH} (with a reference pressure at the nozzle throat P_{TH}) along the divergent section of the nozzle wall for binary nucleation is presented in Fig. 2. The variation is smooth without any jump and is in good agreement with the experimental data.

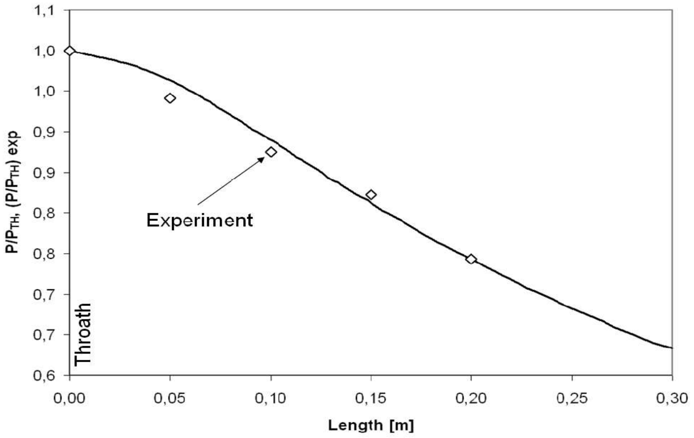

Fig. 2: Relative pressure P/P_{TH} along the straight wall of the divergent section of the nozzle.

Fig. 3 shows subcooling under SSL for expansion of water steam with and without NaCl impurity. The maximum subcooling of pure water steam is much higher $(T_{SSL} - T)_{max} = 27$ K and at the nozzle outlet reminds subcooling of $(T_{SSL} - T) = 2.5$ K.

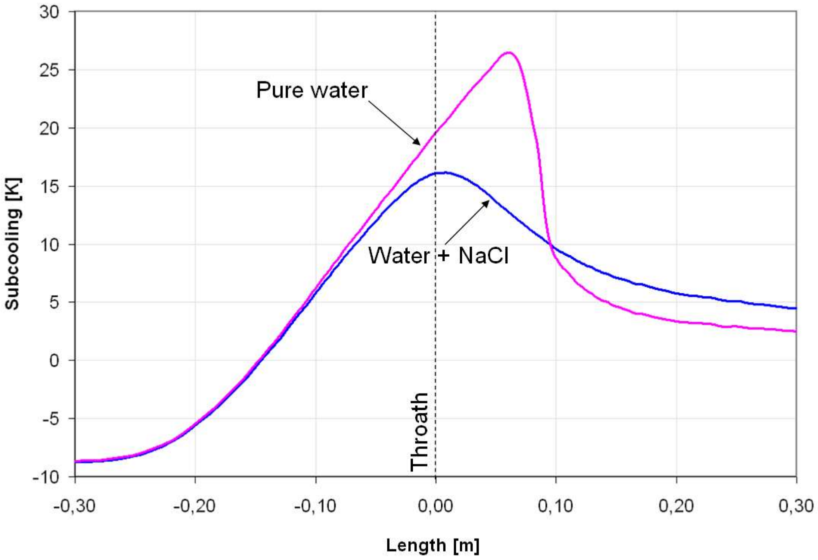

Fig. 3 Subcooling under SSL (T_{SSL}-T) along the nozzle straight wall

The binary nucleation zone is wide. The maximum steam subcooling under the SSL is $(T_{SSL} - T)_{max} = 16$ K and at the nozzle outlet there remains a subcooling of $(T_{SSL} - T_e) = 4.5$ K.

Near the nozzle outlet the heterogeneous droplets reach a mean size of about $R_{2p} = 0.21\times10^{-6}$ m. The measured Sauter mean radius in the experimental nozzle was $R_{32} = 0.14\times10^{-6}$ m. These radii are similar. The difference is probably connected with the difference between the actual experiment and the impurity value in the calculations.

4.3 The Turbine Blade Cascade and Flow Modes

The binary nucleation numerical model was also applied to the calculation of the flow with condensation in a 2D nozzle-blade cascade used in the first wet stage of the LP part of a 200 MW steam turbine. The mid-span profile was chosen for the study and its shape is clear from Fig. 4. The profile chord is 0.181 m and the inlet total pressure and temperature for the designed full turbine output are P_{at} = 71,500 Pa and T_{at} = 373.3 K. The static pressure at cascade outlet for full turbine output is p_e = 34,300 Pa.

From the inlet total conditions it follows that the inlet superheat is $(T_{at} - T_s)$ = 9 K. The Mach number downstream of the cascade assuming isentropic flow is $M_{eis} \cong 1.10$. The flow in the cascade is therefore transonic and steam condensation occurs.

Calculations were also performed for a flow with a lower expansion rate and a higher outlet static pressure of p_e = 44,500 Pa. The flow in this case is subsonic ($M_{eis} \cong 0.87$).

4.4 Calculation Results for a Cascade Outlet Static Pressure of p_e = 34,300 Pa (M_{eis} = 1.10).

The expansion of the steam in the cascade is shown by the isolines of Mach number in Fig. 4. The flow velocity in the blade passage increases gradually without any jump and at the throat the Mach number reaches a value of M_{TH} = 1.00. Downstream of the throat, the flow is transonic with a typical configuration of exit shock waves. The highest Mach number, M_{max} = 1.20, is reached on the profile suction side.

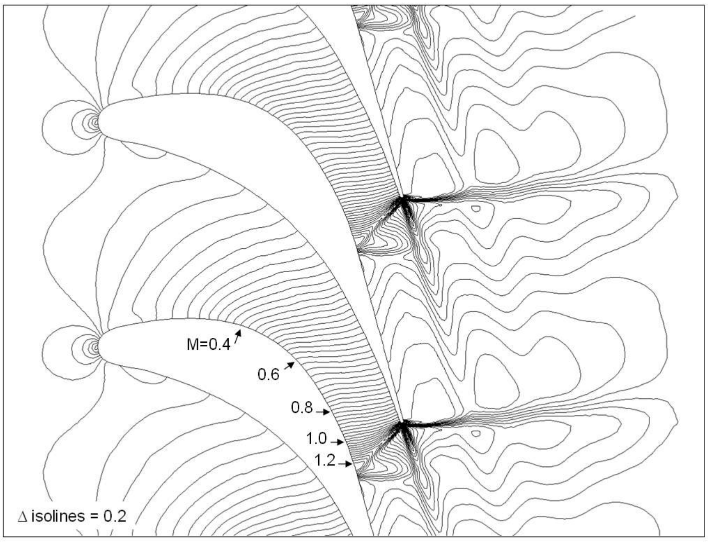

Fig. 4: Mach number M. ΔM of isolines = 0.02

Figure 5 shows the variation of the expansion rate along the profile starting at the trailing edge and moving around the blade along the suction side. The peak value on the suction side of the blade is $P_{r,max} \cong 13{,}000\ \text{s}^{-1}$ and on the pressure side at the trailing edge $P_{r,max} \cong 6500\ \text{s}^{-1}$. This values are very high.

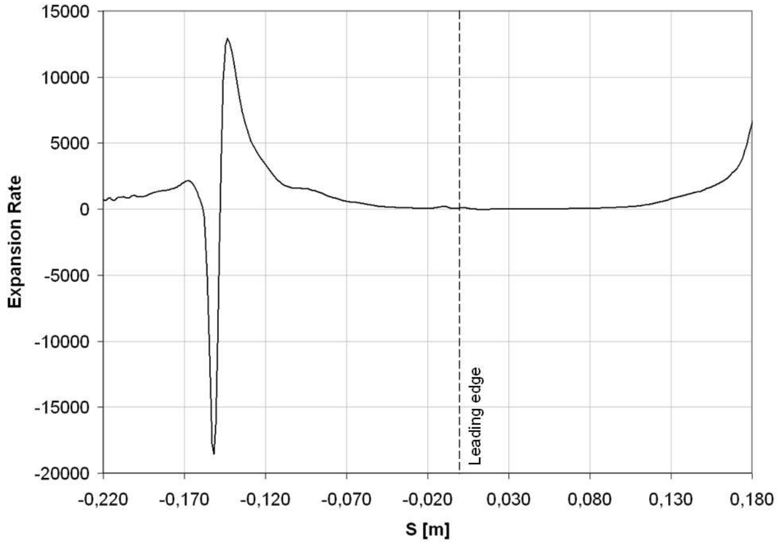

Fig. 5: Expansion rate P_r along the profile

Downstream of the nozzle blade cascade, the heterogeneous droplets reach a maximum mean size of about $R_{2p} = 0.008\times10^{-6}$ m. The embryo number produced by binary nucleation has a maximum value downstream of the nozzle blade cascade of about $Q_{0p} = 4.77\times10^{18}$ kg^{-1}. For this specific number of heterogeneous droplets it would be necessary for there to be more than 463 μg of NaCl per kg of steam in molecular form. This is not realistic.

4.5 Calculation Results for a Cascade Outlet Static Pressure of p_e = 44,500 Pa (M_{eis} = 0.87).

Figure 6 shows the variation of the expansion rate along the profile starting at the trailing edge and moving around the blade along the suction side. The peak value on the suction surface is $P_{r,max} = 4100$ s^{-1} and on the pressure side at the trailing edge $P_{r,max} = 5000$ s^{-1}. These values of the expansion rate are much lower than those in the nozzle mentioned above.

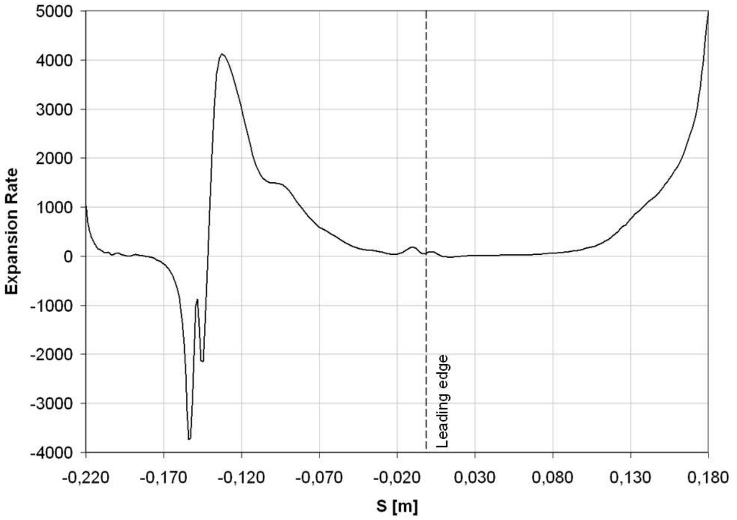

Fig. 6: Expansion rate P_r along the blade surface.

The distribution of the subcooling under the TPB of NaCl is shown in Fig. 7. The three-phase boundary is situated in the front part of the blade passage and the binary nucleation starts there. The subcooling under the TPB gradually grows and just beyond the throat it reaches a maximum value of $\Delta T_{NaCl,max}$ = 32.9 K.

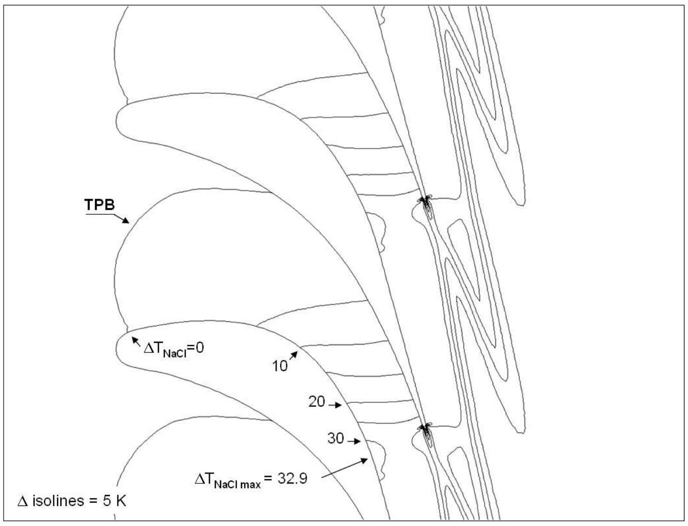

Fig. 7: Subcooling ΔT_{NaCl} [K] under the TPB. ΔT of isolines = 5 K.

The distribution of the subcooling under the SSL is shown in Fig. 8. The steam saturation line lies in the central part of the blade passage. The subcooling under the SSL gradually grows and reaches a maximum value of ΔT_{max} = 25.4 K just beyond the throat. At the cascade outlet there is a slight residual subcooling of $(T_{SSL} - T_e)$ = 0.04 K.

The position of the salt solution zone (SSZ) is located between the zero value of the subcooling contour under the TPB (see Fig. 7) and the zero value of the subcooling contour under the SSL (see Fig. 8). In the SSZ there can be embryos or droplets containing NaCl molecules.

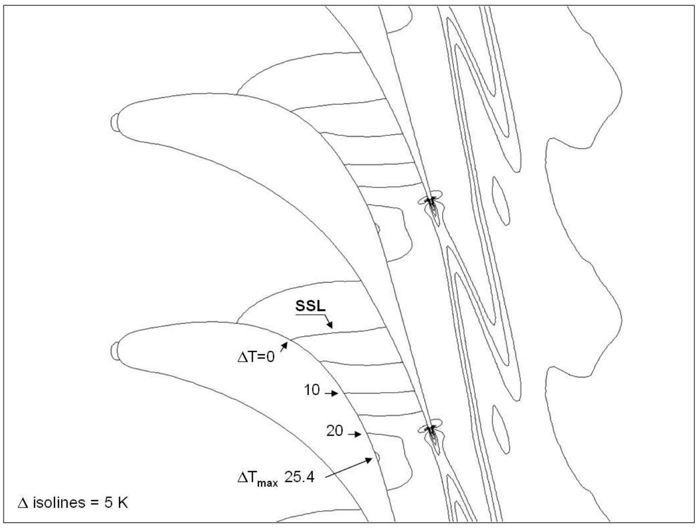

Fig. 8: Subcooling ΔT [K] under the SSL. ΔT of isolines = 5 K.

The first noticeable wetness occurs downstream of the trailing edges. As shown in Fig. 9 the heterogeneous wetness then quickly grows and reaches a value of $y_p = 1.4$ %.

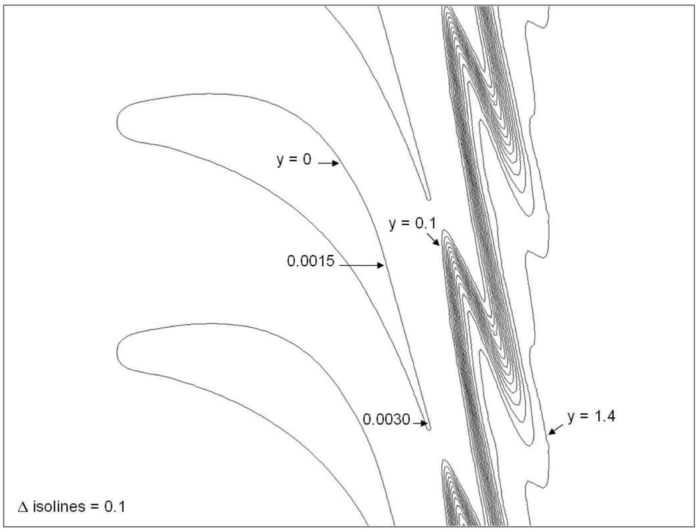

Fig. 9: Heterogeneous wetness y [%]. Δy of isolines = 0.1 %.

Downstream of the cascade the heterogeneous droplets reach a maximum mean size of about $R_{2p} = 0.055\times10^{-6}$ m. The embryo number produced by binary nucleation has a maximum value downstream of the cascade of about $Q_{0p} = 1.73\times10^{16}$ kg^{-1}. For this specific number of produced droplets it is necessary for there to be more than 1.7 μg of NaCl per kg of steam in molecular form.

5 ANALYSIS OF RESULTS AND CONCLUSIONS

A mathematical model for condensation based on the binary nucleation of the chemical impurity NaCl and water, with subsequent water condensation on the nucleated droplets has been briefly described.

The binary nucleation numerical model has been tested by calculating the flow with condensation in a nozzle with a low expansion rate of about $P_r = 1000$ s^{-1} in the divergent part. The flow with binary nucleation is smooth without any condensation shock and pressure jump. The pressure variation is in good agreement with the data obtained from experiments with low steam purity.

The binary nucleation model has also been applied to the turbine nozzle-blade cascade of the first wet stage. The flow regime in the cascade with an outlet pressure of $p_e = 34{,}300$ Pa corresponds to the designed full turbine output. The flow in the cascade is then transonic with outlet shock waves. The maximum value of the expansion rate is very high, $P_{r,max} = 13{,}000$ s^{-1}. The produced droplets are very small and their specific number is abnormally high $Q_{0p} = 4.77\times10^{18}$ kg^{-1}. For this specific number of droplets it would be necessary for there to be more than 463 μg of NaCl per kg of steam in molecular form, and this is not realistic. The maximum guideline value for steam in turbines is NaCl < 5 μg/kg of steam. For this flow regime there cannot be significant binary condensation in the cascade, but spontaneous condensation does occur.

In the case of a higher pressure at cascade outlet, $p_e = 44{,}500$ Pa, the flow is subsonic and the maximum expansion rate is much lower, $P_{r,max} = 4100$ s^{-1}. The subcooling under the SSL is also lower, $\Delta T_{max} = 25.4$ K. The droplets produced are bigger and their specific number is about two orders lower, $Q_{0p} = 1.73\times10^{16}$ kg^{-1}. For this specific number of produced droplets it is necessary for there to be more than 1.7 μg of NaCl per kg of steam in molecular form. The outlet heterogeneous wetness is lower and, for this flow regime, binary condensation in the turbine cascade may prevail.

It is recommended to situate the SSZ of NaCl in a turbine cascade with a lower expansion rate and to realize there primarily a binary nucleation of steam and NaCl for the initial condensation. As a consequence, the steam subcooling and the thermodynamic loss will be lowered in the first wet stage.

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