CONDENSATION OF STEAM
in nozzles and turbine cascades

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This “late harvest” is dedicated to my wife for her patience with my research work.

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1. INTRODUCTION

The process of condensation of the steam flowing through the LP part of a turbine is evidently the last mystery of steam turbines. It has already been treated by Stodola [26]. The condensation is a complicated process, and considerable unwanted effects occur - stress corrosion of blades and rotors in the Phase Transition Zone of the flow path, the erosion of moving blades of the last stages and a drop of efficiency of the wet stages. The problems of condensation in steam turbines are still topical – see the “Baumann Centenary Conference”, Cambridge 2012 [30, 31].

The experiments performed in converging diverging (CD) nozzles with higher expansion rates allowed the understanding of the homogeneous condensation of the flowing steam in more detail. It was understood that homogeneous condensation in steam turbines should occur suddenly at the Wilson line with sufficient subcooling of the steam and at corresponding values of equilibrium wetness about y = 3 % - see Gyarmathy [16].

Measurements carried out in turbines did not fully confirm the conclusions from the CD nozzle measurements and indicated that the condensation can run more uniformly. Steltz, Lee and Lindsay [25] have proved the existence of the so called „Salt Solution Zone“ in steam turbines. Nucleation and condensation occur above the saturation line in the superheated zone on molecules of NaCl, Na_2SO_4, etc. The presence of heterogeneous condensation was confirmed by experiments with a model steam turbine by Dibelius et al. [6] and with full scale turbines by Walters, Langford [28] and others.

From the summary of the existing knowledge it appears that in the LP part of the steam turbines homogeneous condensation and heterogeneous condensation are running in parallel. The latter is dependent on the impurities in the steam and prevails when there is a high content of impurities.

Experiments with the effects of various chemicals on the flow with condensation in a convergent-divergent nozzle were performed as part of the international project “Steam, Chemistry, and Corrosion in the Phase Transition Zone of Steam Turbines” [5]. Petr and Kolovratník performed the experiments at the Czech Technical University (CTU) experimental facility in Prague, Czech Republic.

The 2D computational model and the COCHEM Flow code were developed for a more detailed understanding of the condensation process and of the behaviour of corrosive salts in the blade cascades. This enabled the numerical modelling of the flow with homogeneous condensation, the simulation of the heterogeneous condensation, the description of the precipitation of corrosive salts (NaCl) in the superheated steam and the presence of droplets with salt content (NaCl) in the Salt Solution Zone.

2. STEAM EXPANSION IN PHASE TRANSITION ZONE

2.1. Expansion with hetero-homogeneous condensation

The real steam expansion lines, based on measurements in a 200 MW steam turbine, can be seen in the enthalpy-entropy diagram shown in Fig. 2.1.1.

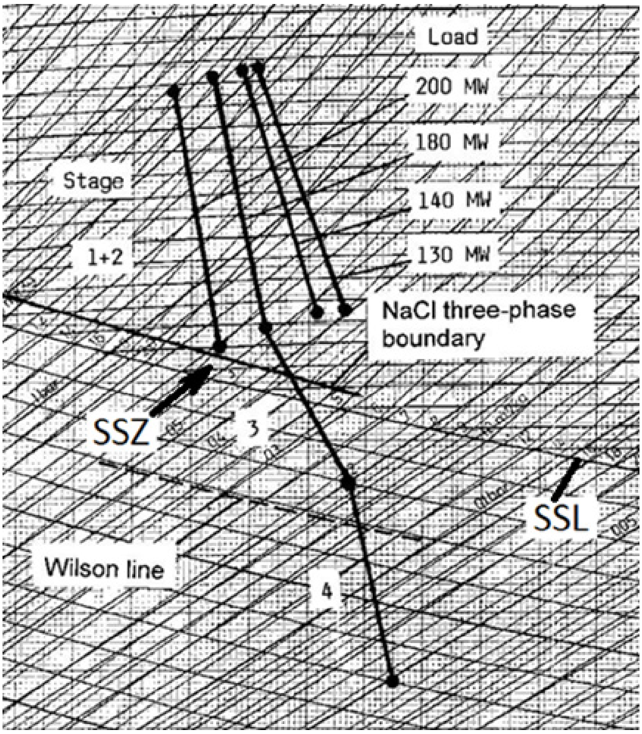

Fig. 2.1.1. Enthalpy-entropy diagram of the steam expansion in the LP part of a 200 MW turbine.

It can be seen in the enthalpy-entropy diagram that the steam expansion line for 180 MW load intersects the NaCl three-phase boundary (TPB), passes through the salt solution zone (SSZ) and intersects the steam saturation line (SSL). All these effects appear in the third (L-1) stage. The expansion in this stage shows an important increase of entropy as a consequence of the thermodynamic loss and subcooling of the steam.

The Wilson line for spontaneous condensation is also drawn in the diagram. It is based on measurements performed by Gyarmathy and Meyer [11] in nozzles for expansion rates in the range $P_r = 1000 – 5000\ s^{-1}$. The corresponding equilibrium wetness at the Wilson line is $y = 3.1 \pm 0.2\ \%$. It follows that the phase transition zone, from the top at the TPB down to the Wilson line, is here situated in the L-1 stage and partly in the final (fourth) stage.

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) with 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) 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 of 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 computational model includes the homogeneous condensation of droplets and heterogeneous condensation on the droplets that are created in the Salt Solution Zone. This is the model of hetero and homogeneous condensation.

The basic ideas of the computation model are obvious from the transonic steam expansion in the blade cascade in the phase transition zone with the presence of chemical impurities in the steam - see Fig. 2.1.2.

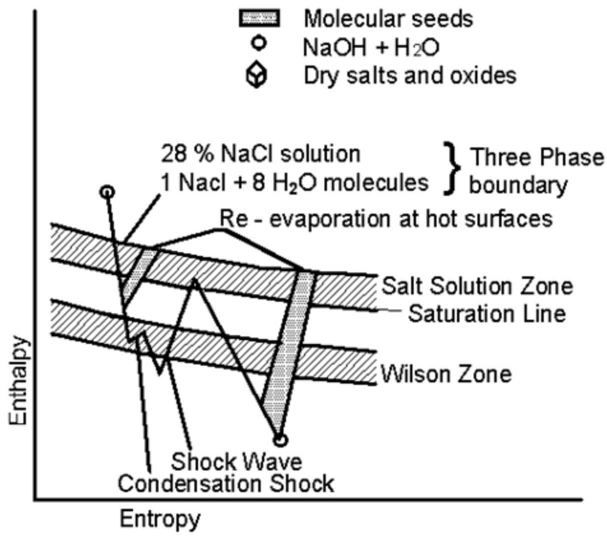

Fig. 2.1.2. Steam expansion line and chemical impurities in phase transition zone.