Experimental research on coarse water formation in steam condensing flow on a transition through the shock wave

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Abstract. In this work the condensation phenomena in steam turbine were discussed. The motivation for presented research was an interaction of liquid phase with shock waves existing in the transonic flow. The paper presents the experimental results of the steam condensing transonic flow in Laval nozzles. For the tests the geometries of the half arc nozzles were used. The behaviour of shock waves in the wet steam region was investigated. Due to the high back pressure, in the divergent part of the nozzle the shock wave was induced and interacting with the nozzle walls caused instability in the flow.

1. Introduction

Condensation, i.e. the phase change of steam to liquid water occurs in a number of engineering applications. Condensation of steam is in many applications desired, such as in heat exchangers or steam condensing turbine. The condensation process in steam turbines takes place in the last stages of the low-pressure part by very high steam velocity, in transonic flow conditions. Condensation of steam occurs when the temperature drops below the saturation temperature at a given pressure, i.e. the saturation line. Latent heat is released from liquid water as the phase change occurs, this heat has to be taken over by surrounding vapour phase. Since the phase change affects pressure, temperature, velocity and heat transfer a lot of work has been done in experimental investigation [1, 2, 3, 4, 5] and computational modelling [6, 7, 8, 9] of condensation.

The process of condensation can be divided into primary (homogeneous/heterogeneous) condensation and surface condensation. Numerous methods exist to determine primary condensation that occurs in the steam flow [10, 11], while the modelling of condensation onto a surface is by no means trivial.

Primary condensation is the phenomena where droplets grow in size in supercooled vapour in a free flow. The liquid phase consists of the small droplets (0.1–0.001 μm) forming a fog. Supercooling is the difference between the saturation temperature at the given pressure and vapour phase temperature. If small foreign particles exist in the steam, these will serve as condensation nuclei. The heterogeneous condensation mainly consists of droplets growth process only. Saturation lines of many admixtures (NaCl, HCl, NaOH, and other) dissolved in the steam are located higher than that for pure steam [12], therefore, droplets of these admixtures can act as condensation nuclei, thus causing the condensation front to shift toward the point of less supercooling.

The homogeneous condensation takes place in the absence of foreign particles, where due to the rapid expansion of the flow the nucleation process occurs, i.e. the formation of critical droplets, on which the further droplets growth is continued [1, 13]. When pure steam expands in the turbine flow path, its

condensation in the flow occurs with relatively high supercooling (by approximately 30-35°C) and the front of initial condensation is located within the so called Wilson's zone, which corresponds to an equilibrium steam wetness of 2.5-3.5%.
As water vapour comes into contact with a surface at a temperature below the saturation temperature for the corresponding partial pressure of the water vapour, droplets start to form on the surface. As the water condensate on the cooled surface, the latent heat is released onto the surface. The thickness of the water film depends also on the surface roughness. The condensation on the steam turbine blade surface can occur at a very small level of supercooling and even with some steam superheating, +0.3 ÷ –0.3°C. The water film thickness for a curvature radius of the surface roughness of 1 μm is in the range of 0.1-0.001 μm. The above values of the film thickness are of the same order of magnitude as the radius of the droplets formed in the primary condensation front region.

2. Motivation

As it was already mentioned, the liquid phase formation occurs by a very high steam velocity, even supersonic. Usually, for the nominal load of the steam turbine the primary condensation takes place in the stator of the low-pressure part last stage. For the stator blades the transition from sub- to supersonic flow conditions and primary condensation onset correspond to the area between the upper blade trailing edge and the bottom blade suction (convex) side surface (figure 1). The oblique shock wave set comprises the so-called fishtail shock starting downstream of the trailing edge of the blade and the shock wave reflected from the suction side.

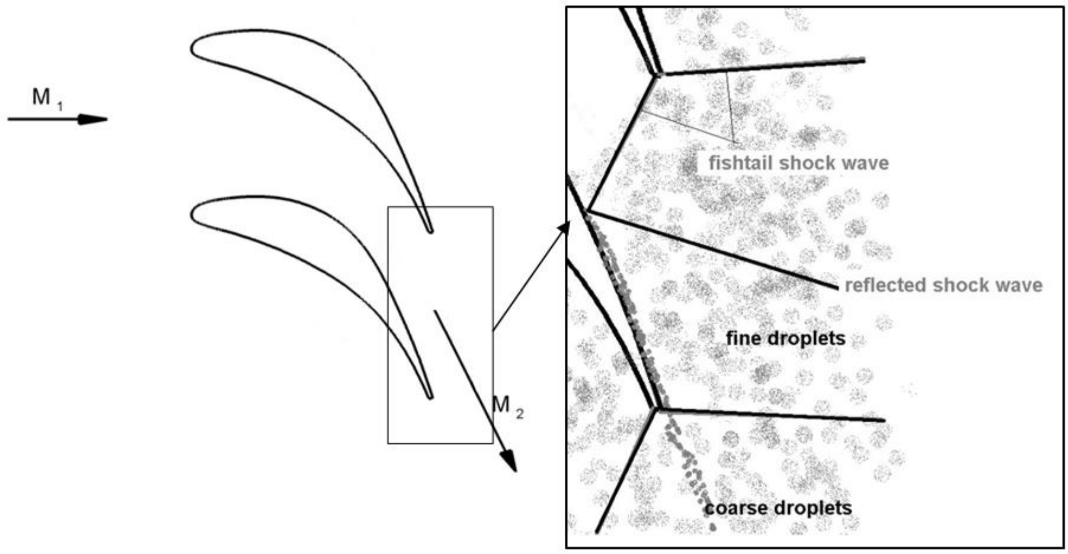


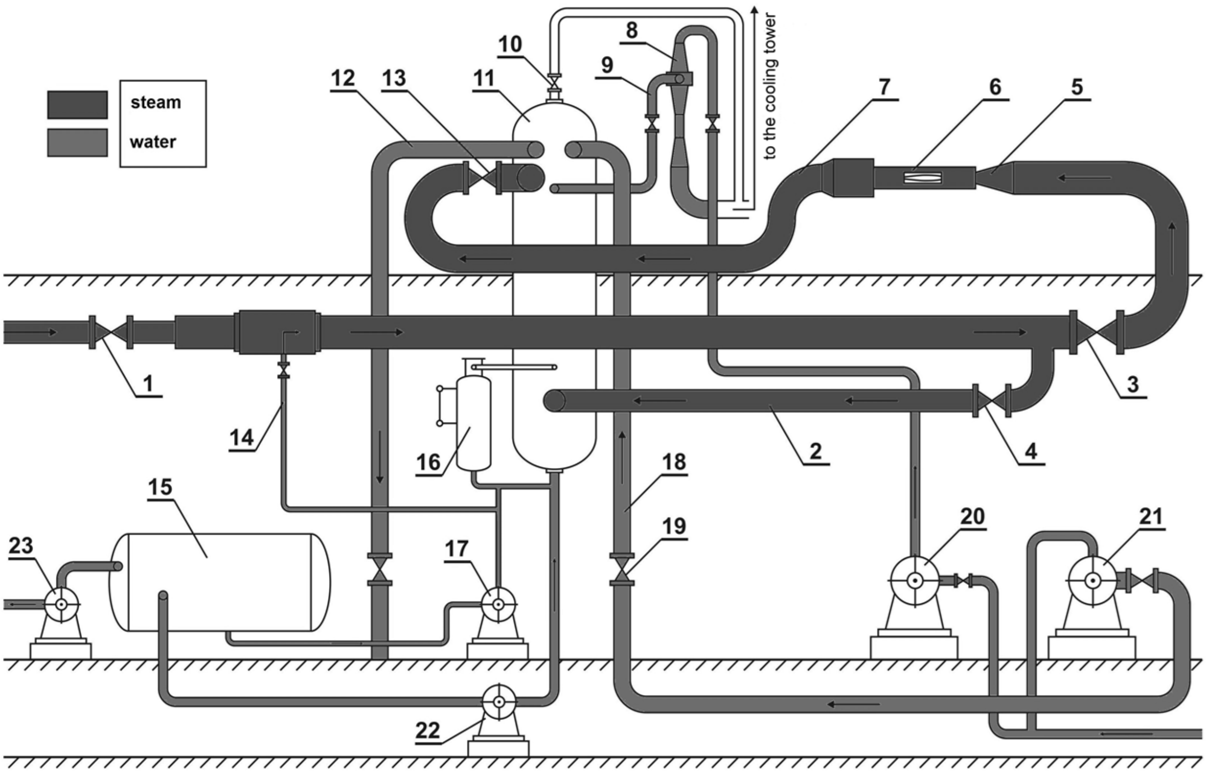
Figure 1. Sketch of the shock waves configuration in blade-to-blade channel for the turbine stage stator (M – Mach number).

The liquid film forms on the suction side surface and leaves the blade together with flowing steam, forming the coarse water droplets behind blade.
Very important issue is the behavior of the fine droplets on the transition through the shock waves. On the shock wave transition, we deal with the rapid increase of the pressure and temperature and decrease of velocity. The fine droplets have a slightly higher temperature and pressure and move with a little smaller velocity than the surrounding vapour phase, therefore, it is expected that the part of the droplets evaporate on the shock wave and they start colliding between each other in the result of the rapid slowing down.
Generally, the interaction of the shock wave with a solid surface causes, in the most cases, separation of the boundary layer [14]. These phenomena have a significant (typically negative) impact on the

flow, especially when there is a liquid film on the solid surface. The interaction of the liquid phase, fine or/and coarse droplets, with the shock waves in supersonic flow affects the unsteadiness. The numerical modelling of this phenomenon is very difficult and requires to use a two-fluid model [10] including both mentioned condensation processes, also model of water droplets collision and coagulation. Additionally, for the elaboration and validation of such model the experimental data are necessary. The main motivation of presented work is to experimentally investigate the interaction of the shock wave with liquid phase in steam condensing transonic flow. To this end the flow through the Laval nozzle was taken into account and the shock wave was generated by increasing the pressure at the nozzle outlet.

3. Experimental facility

The experimental facility is a part of the small steam condensing power station that is located in the Institute of Power Engineering and Turbomachinery of the Silesian University of Technology. The steam tunnel facility (figure 2) was designed in order to perform the experiments for steam condensing flows in nozzles or linear cascades [15]. The superheated steam of the very stable parameters is supplied from the 1MWt boiler. The maximum steam mass flow rate is about 3 kg/s. The parameters ahead of the test section are controlled by means of the control valve and desuperheater providing the steam with parameters corresponding to the conditions prevailing in low-pressure turbine stages. The total inlet pressure can vary in the range of 70-150 kPa(a) and the total temperature between 70-120°C. The pressure behind the test section is controlled by the throttle valve assuring the corresponding value of the static back pressure.



1) Control valve 2) By-pass 3) Stop gate valve 4) Stop gate valve at by-pass 5) Inlet nozzle 6) Test section 7) Outlet elbow 8) Water injector 9) Pipe 10) Safety valve 11) Condenser 12) Suction line 13) Throttle valve 14) Desuperheater 15) Condensate tank. 16) Control system of condensate level. 17) Condensate pump 18) Discharge line 19) Stop valve 20) Water injector pump 21) Cooling water pump 22) Condensate pump 23) Pump

Figure 2. Steam tunnel with auxiliary devices.

4. Experimental results

The experimental measurements were performed for the geometry of the half Laval nozzle. The applied half nozzle is an arc nozzle with lower critical throat height of H* = 27.5 mm and wall curvature radius of R = 525 mm (figure 3). The width of the nozzles amounted to 110 mm. The static pressure measurement in the nozzles was carried out on a distance of 200 mm downstream from the nozzle throat along the line in the middle of the nozzle width. The distance between pressure taps was 10 mm. Each measurement series lasted 30seconds and the static pressure was measured with the frequency of 400 Hz, what gave the total value of 12000 samples. The accuracy of the applied pressure transducers (Honeywell 243PC15M) was ±100 Pa. This accuracy was achieved by individually calibration of the pressure transducers within the range of 0÷100 kPa(a).

The measurement uncertainty within one series was calculated as a difference between maximum and minimum value plus accuracy of the sensor. The length of the pressure tubes connecting the pressure transducers with the taps was about 200 mm, what is too big value in order to capture the flow unsteadiness in high accuracy.

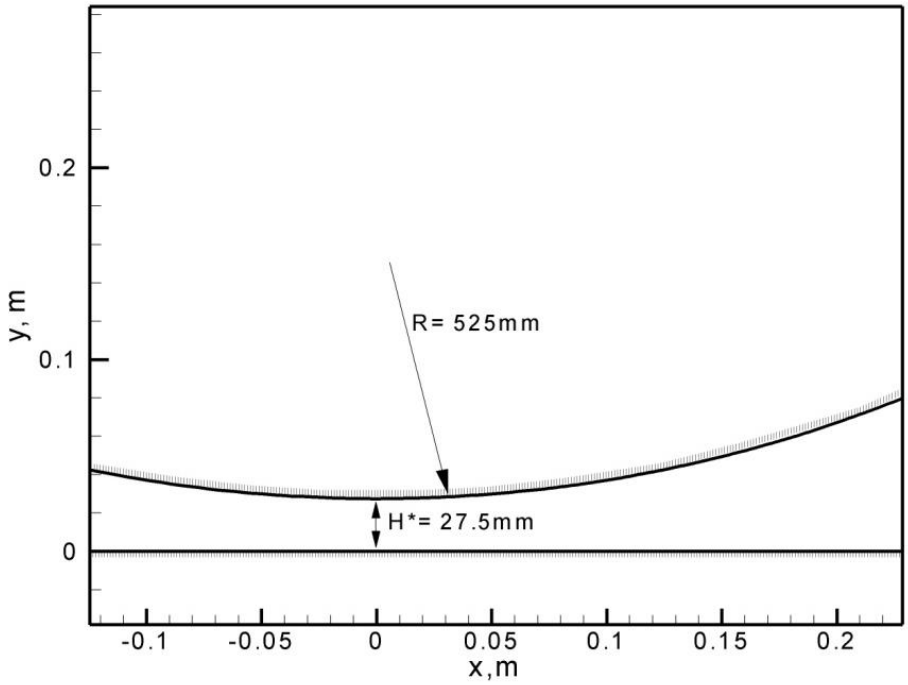


Figure 3. Geometry of the half arc Laval nozzle.

For nozzle at the inlet the value of total pressure was $112500^{\pm 250}$ Pa(a) and temperature of $111^{\pm 0.25}$ °C. The back pressure value amounted to 50000 Pa(a).

Figure 4 shows the observed water membrane created on the shock wave. This phenomenon was visible by naked eye, without additional flow visualisation techniques.

In order to explain the appearance of water film on the shock wave the sketch presented in the figure 5 may be useful. Figure 5 depicts the possible configuration of the shock waves in the nozzle caused by too high back pressure.

It can be conclude that the one possible reason for creating the observed water film is the rapid retardation of the fine droplets on the transition through the shock wave. It contributes to the collision and coagulation of the fine droplets, finally creating the coarse droplets behind the shock wave.

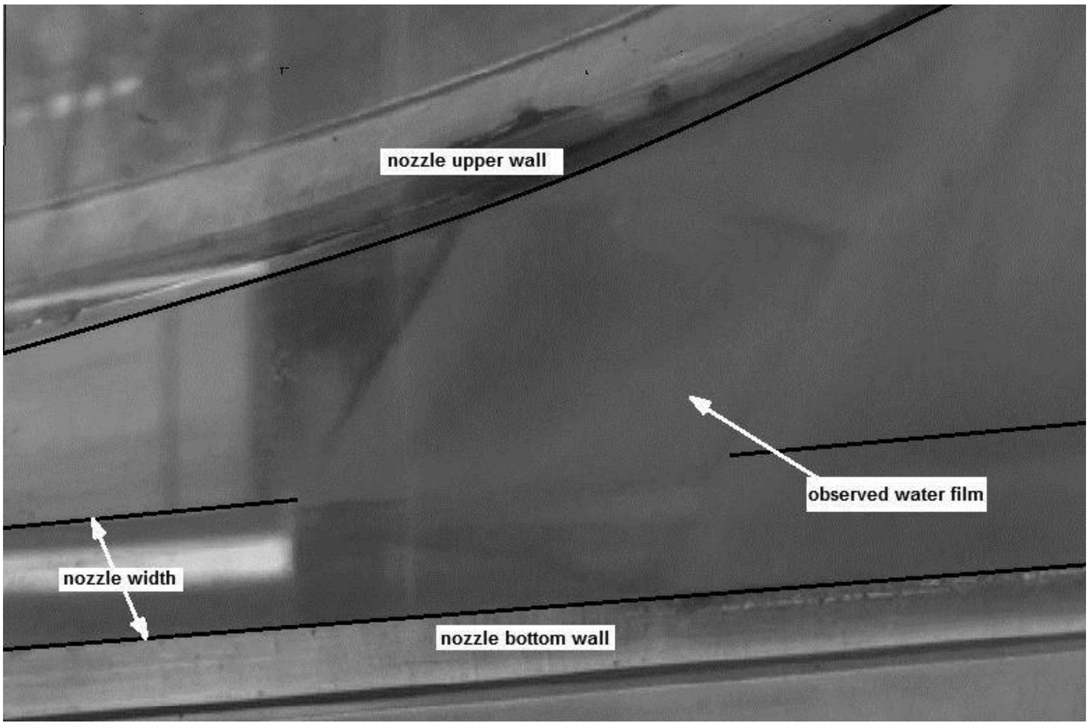


Figure 4. Photo of the observed water film on the shock wave.

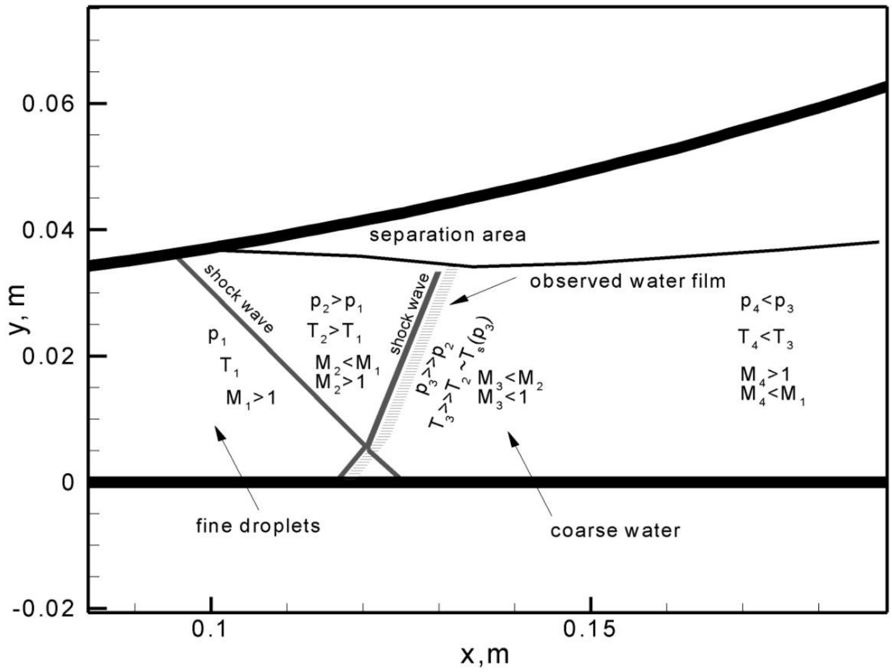


Figure 5. Sketch of the shock waves configuration caused by high back pressure in supersonic part of the Laval nozzle (*M – Mach number, p – static pressure, T – static temperature*).

Figure 6 presents the values of measured static pressure together with measurement uncertainty along the bottom wall of the nozzle. It is visible that in the vicinity of the shock wave the measurement uncertainty rapidly increases. It is caused by the interaction of the shock wave with the water film on the bottom and top walls and chaotic movement of the coarse water behind the shock.

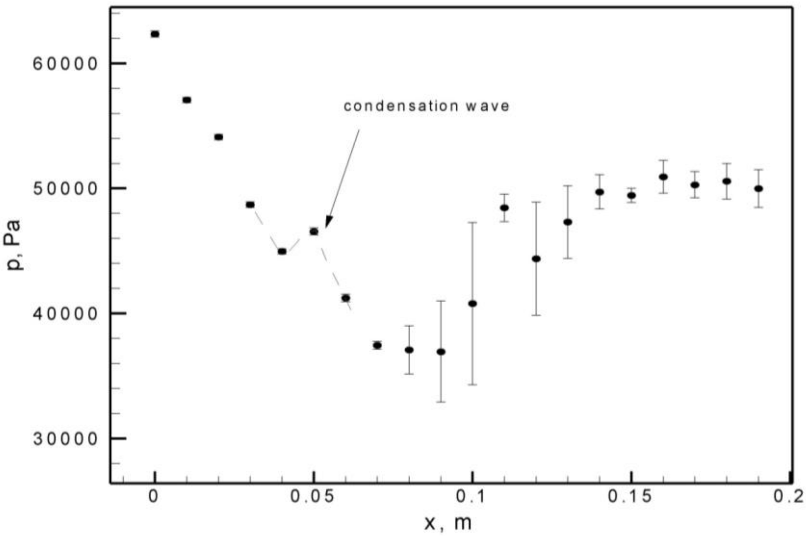


Figure 6. Measured static pressure distribution along the bottom wall of the nozzle *(p – static pressure*).

In spite of too long pressure tubes that were applied in experiment the dominated frequency of the unsteadiness appearing in the shock wave vicinity was a little above 100 Hz (figure 7). The value of this frequency depends on the flow conditions as well as the nozzle geometry (expansion rate $\dot{P} = -\frac{1}{p} c \frac{dp}{dx}$, where c is the speed of sound).

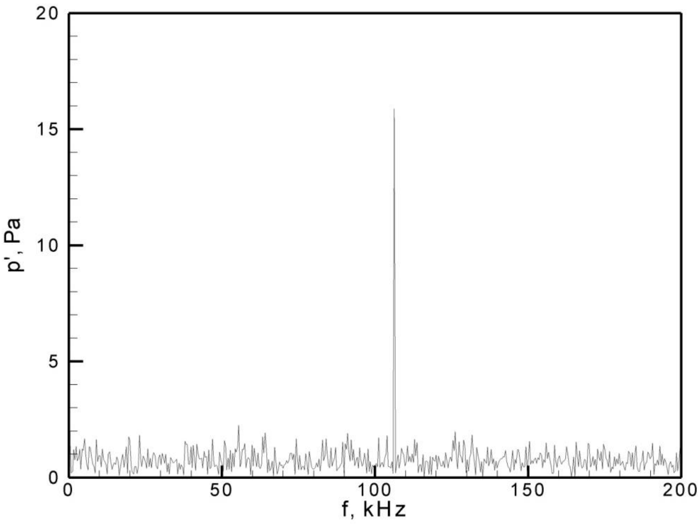


Figure 7. FFT analysis of the static pressure fluctuation on the bottom wall for a position *x = 0.1 m* (*p' – pressure fluctuation*).

5. Conclusions

The paper presents the experimental results of a steam condensing flow in the Laval nozzles. The effect of condensation phenomena and the shock wave behaviour in the wet steam region were investigated.

The obtained experimental results led to the following conclusions:

- On a strong shock wave the water film (water membrane) was observed by naked eye that was created due to the strong retardation of the fine droplets created in the results of primary condensation.
- Behind the water film observed on the shock wave the coarse water droplets are created that were formed in the result of collision and coagulation of the fine droplets. The coarse water moves in the chaotic way.
- The experiments of the shock wave behaviour in the wet steam region showed a coarse water formation in detachment zone, i.e. in the place of the shock wave interaction with the solid wall.
- The coarse water formation and its chaotic movements cause the flow unsteadiness with the frequency of hundreds hertz, this value depends mainly on the expansion rate (nozzle geometry and boundary conditions at the nozzle inlet).

The future experimental work will concentrate on a detailed explanation of the phenomenon of coarse water formation in separation region caused by shock wave. This phenomenon can be crucial for further research in nozzle but in particular in linear cascades. Also, obtained experimental data will be helpful in the future work on a numerical model, its validation.

6. References

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