Symkom 2014 Open Access

Mirosław Majkut*, Sławomir Dykas, Michał Strozik, and Krystian Smołka

Experimental and numerical study on condensation in transonic steam flow

DOI 10.1515/eng-2015-0035

Received January 07, 2015; accepted May 20, 2015

Abstract: The present paper describes an experimental and numerical study of steam condensing flow in a linear cascade of turbine stator blades. The experimental research was performed on the facility of a small scale steam power plant located at Silesian University of Technology in Gliwice, Poland. The test rig of the facility allows us to perform the tests of steam transonic flows for the conditions corresponding to these which prevail in the low-pressure (LP) condensing steam turbine stages. The experimental data of steam condensing flow through the blade-to-blade stator channel were compared with numerical results obtained using the in-house CFD numerical code TraCoFlow. Obtained results confirmed a good quality of the performed experiment and numerical calculations.

Keywords: wet steam; condensation; experiment; numeric; linear cascade

1 Introduction

In steam turbines of a large output, the expansion line usually crosses the saturation line in penultimate stages. It means that at least last two stages of the low-pressure steam turbine operate in the two-phase region, producing much more than 10% of the total power output. The condensation process in steam turbines takes place in the last stages of the low-pressure part at a 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 [1–3] and computational modelling [4–8] of condensation.

The homogeneous (rapid or primary) condensation is the phenomenon where droplets grow in size in supercooled vapour in a free flow. The liquid phase consists of small droplets (0.1–0.001 μm) forming a fog. 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 further droplets growth is continued [9, 10]. 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 condensates 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 K. 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. The water film on the blade surface makes a lot of problems in experimental research that is carried out in the Institute of Power Engineering and Turbomachinery.

The presented experimental and numerical research was carried out by means of the in-house facility and in-house numerical CFD code [11–13]. More detailed description of in-house numerical CFD code TraCoFlow is included in the publication [14] .

***Corresponding Author: Mirosław Majkut:** Institute of Power Engineering and Turbomachinery, Silesian University of Technology, Konarskiego 18, Gliwice, E-mail: miroslaw.majkut@polsl.pl
Sławomir Dykas, Michał Strozik, Krystian Smołka: Institute of Power Engineering and Turbomachinery, Silesian University of Technology

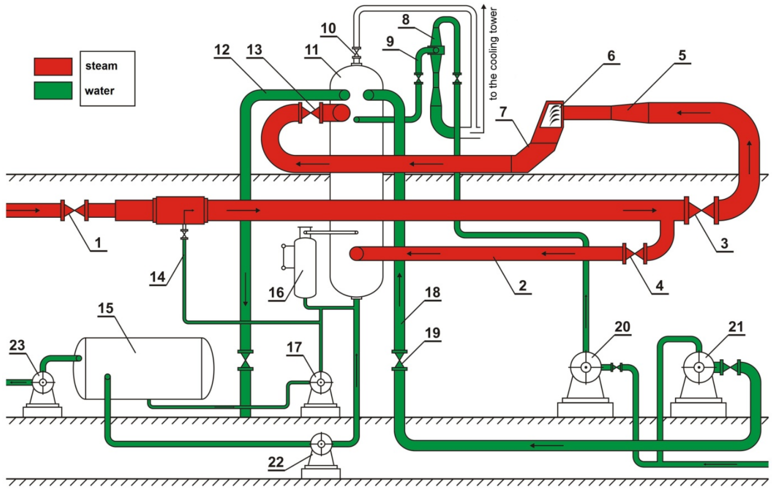


Figure 1: Steam tunnel with auxiliary devices.
1) Control valve 2) By-pass 3) Stop gate valve 4) Stop gate valve at by-pass 5) Inlet nozzle 6) Test section 7) Outlet elbow 8) Water injector 9) Pipe 10) Safety valve 11) Condenser 12) Suction line 13) Throttle valve 14) Desuperheater 15) Condensate tank. 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

2 Experimental facility

The experimental facility is a part of the small steam condensing power plant that is located in the Institute of Power Engineering and Turbomachinery of the Silesian University of Technology. The steam tunnel facility (Figure 1) was designed in order to perform the experiments for steam condensing flows in nozzles or/and linear cascades [13]. The superheated steam of sTable parameters is supplied from the 1 MW_t 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 applied linear cascade (Figure 2) consists of stator blades of geometry corresponding to the last stage of the LP steam turbine (Figure 3). The linear cascade comprises 4 blades what gives 3 blade-to-blade channels. The width of the cascade amounts to about 110 mm.

The static pressure measurement was carried out using the Honeywell 243PC15M pressure transducers. The positions of the pressure taps on the blade surface were depicted in Figure 3. Each measurement series lasted 30 seconds 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 individual 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 the maximum and minimum value plus accuracy of the sensor. By means of the presented test rig it is possible to perform the tests for the wide range of the outlet Mach numbers (Ma=0.8-1.4). In this paper the results for the outlet Mach number Ma=1.2 were presented.

3 Results

During the first part of experimental research static pressure on the suction side close to the predicted condensation wave, were acquired. For this reason the pressure holes 12-19 were used (Figure 3). In the future the static pressure in a whole of 32 pressure taps will be measured.

From the performed experimental tests the results for the inlet total pressure of $91500^{\pm 250}$ Pa(a) and temperature of $101^{\pm 0.25}$°Cwere presented in this paper. The back pressure value for these data amounted to 34500 Pa(a). For these conditions the obtained static pressure data are the closest to numerical results. In the many other tests the presence of the water film on the blade made the comparison with calculations difficult.

By means of the applied in-house CFD code it is possible to model adiabatic and diabatic flow of the wet steam. In the adiabatic case the condensation phenomenon is

CFD model Photo

Figure 2: Investigated cascade chamber.

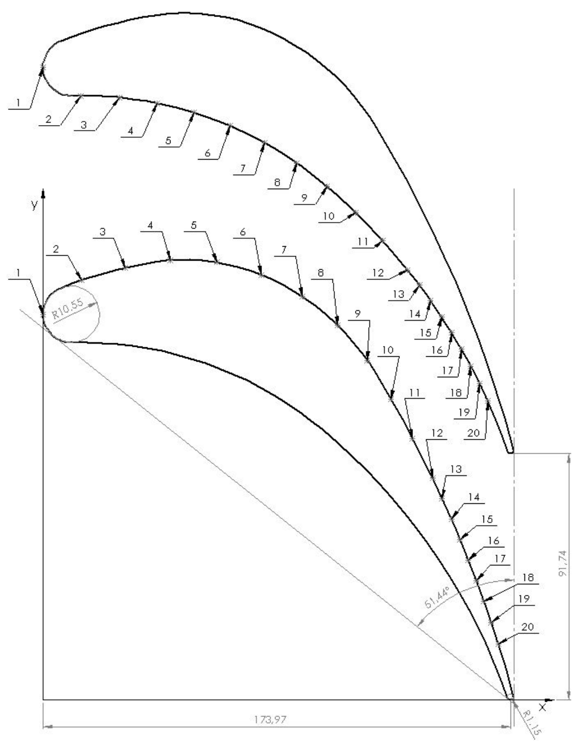
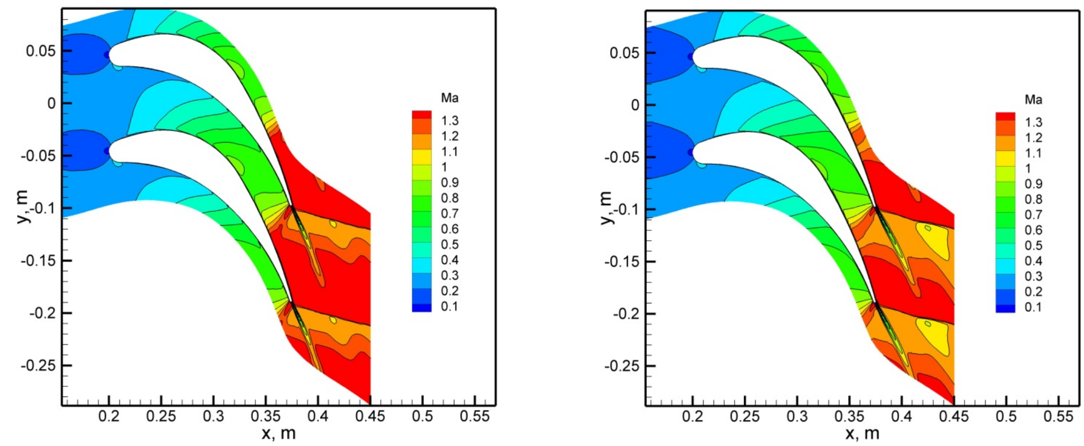


Figure 3: Position of the pressure taps for investigated blade-to-blade channel (Table 1).

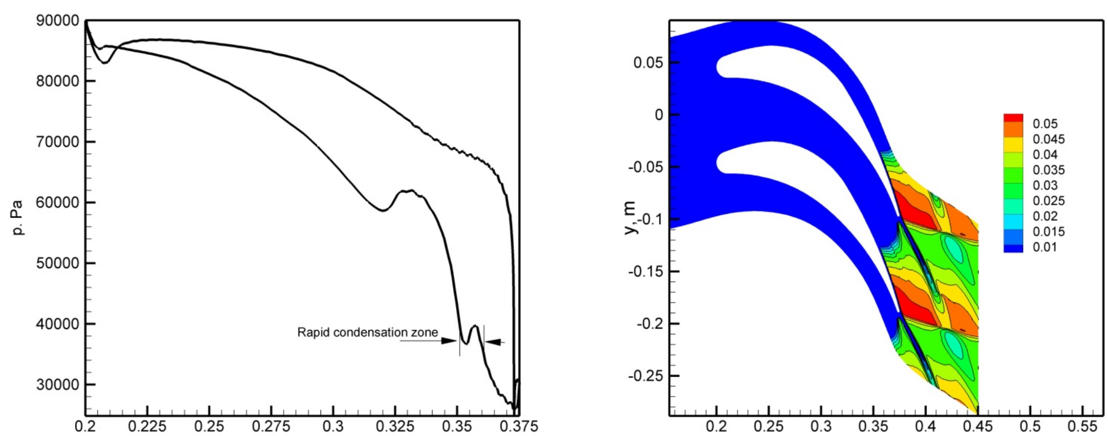
Table 1: Position of the pressure taps for investigated blade-to-blade channel (Figure 3).

	Pressure side		Suction side	
No	x (mm)	y (mm)	x (mm)	y (mm)
1	0	143.45	0	143.45
2	14.1	132.95	14.47	156.15
3	28.3	132.3	30.55	160.71
4	42.38	130.19	47.36	163.46
5	56.16	126.65	64.59	162.75
6	69.52	121.72	81.21	158.12
7	82.28	115.45	96.36	150.05
8	94.35	107.91	109.68	139.29
9	105.63	99.14	120.74	126.24
10	116.23	89.5	129.5	111.89
11	126.24	79.17	137.49	97.34
12	135.57	68.23	144.97	82.5
13	140.01	62.51	148.52	74.95
14	144.22	56.7	151.91	67.4
15	148.25	50.76	155.19	59.74
16	152.05	44.76	158.29	52.1
17	155.66	38.65	161.28	44.37
18	159.08	32.43	164.1	36.66
19	162.36	26	166.8	28.85
20	165.45	19.41	169.36	20.99



Adiabatic Diabatic

Figure 4: Mach number comparison for the flow without and with condensation.



Static pressure on the blade Wetness fraction

Figure 5: Distribution of the calculated static pressure on the blade and wetness fraction for diabatic case.

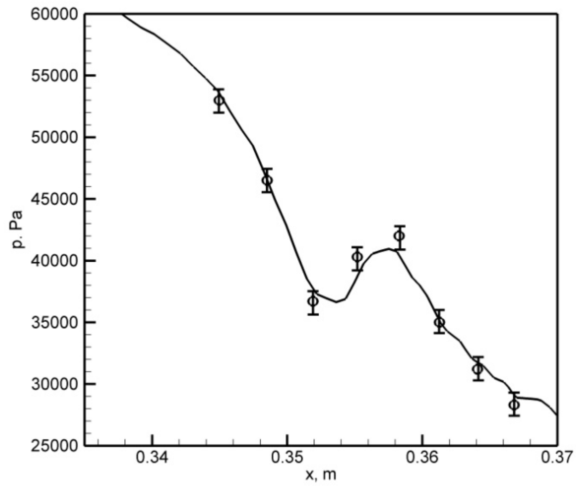


Figure 6: Distribution of the calculated and measured static pressure on the blade. Solid line: calculations, open circles with error bars: experiment.

not taken into account and the steam parameters below the saturation line are extrapolated from the superheated state. In this case we deal with a gas phase only, the liquid phase is not considered. In the diabatic case the liquid phase is created as a result of spontaneous (rapid) condensation.

Figure 4 shows the comparison between the calculated Mach number distribution for the adiabatic and diabatic case. One can observe a visible decrease of the outlet Mach number for the case with homogeneous condensation (diabatic one). The condensation effect contributes to the pressure increase (also generation losses) what implies a velocity decrease.

The static pressure distribution and the wetness fraction obtained from numerical calculations of the steam flow with homogeneous condensation were presented in Figure 5. A condensation wave is located at a distance of x=0.35 m, i.e. shortly behind the shock wave connecting the trailing edge with the blade suction side.

The first tentative experimental data were acquired. The measurement of the static pressure had a relatively high uncertainty, mainly due to the fluctuation caused by the water film interaction with the shock wave. The comparison of the measured static pressure with numerical calculations for considered flow conditions is presented in Figure 6. One can observe a relatively good agreement between numerical results and experimental data, with respect to the position and intensity of the condensation shock.

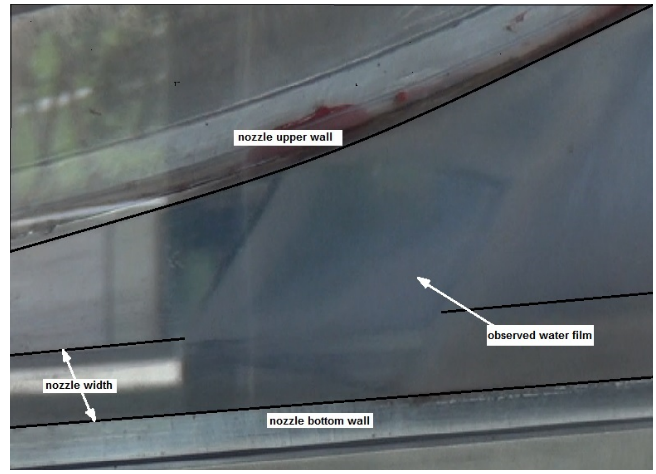


Figure 7: Photo of the observed water film on the shock wave.

4 Final remarks

The presented results are a first step in recognition of the condensation phenomena in the steam flow through blades cascade. It is to contribute to the improvement of the numerical methods for steam condensing flow modelling.

The experiments of the steam condensing flow in a supersonic zone showed a coarse water formation in the vicinity of the shock waves. The presence of the coarse water behind the shock wave is probably caused by the water films separation on the blade suction side. The modelling of the steam condensing flows with coarse water formation needs a much more sophisticated numerical method including modelling the water film formation and its behaviour. Additionally, on a strong shock wave the water film (water membrane) was observed by the naked eye. It was created due to the strong retardation of the fine droplets created as a result of primary condensation. Behind the water film observed on the shock wave the coarse water droplets are also created that were formed as a result of collision and coagulation of the fine droplets. The coarse water moves in the chaotic way. The coarse water formation and its chaotic movements cause the flow unsteadiness. It leads to the significant measurement uncertainty of the static pressure. Figure 7 shows the observed water membrane created on the shock wave in the previous nozzle flow experiments [15]. This phenomenon was visible by the naked eye, without additional flow visualisation techniques. The similar phenomena are very often observed in moist air transonic flows [16].

Future research will concentrate on experiments on a wider range of flow parameters, including the total pressure ahead of the cascade. The Schlieren technique visualization is planned to be used, which creates additional opportunities for the comparison of the experimental data with numerical calculations.

Acknowledgement: The presented work was supported by the National Science Centre founds within the project No. 2011/03/B/ST8/06425

References

[1] Krol T., Results of Optical Measurement of Diameters of Drops Formed due to Condensation of Steam in a Laval Nozzle. Trans. Inst. Fluid Flow Machinery (Poland), 1971, 57, 19–30.

[2] Moses C.A., Stein G.D., On the growth of steam droplets formed in a Laval nozzle using both static pressure and light scattering measurements. ASME, 1978, 100, 311–322.

[3] White A.J., Young J.B., Walters P.T. Experimental Validation of Condensing Flow Theory for a Stationary Cascade of Steam Turbine Blade. Philos. Trans. R. Soc. Lond. A, 1996, 354, 59–88.

[4] Bakhtar F., White A.J., Mashmoushy H., Theoretical treatments of two-dimensional two-phase flows of steam and comparison with cascade measurements. Proc. Inst. Mech. Eng. C J. Mech. Eng. Sci., 2005, 219(C12), 1335–1355.

[5] Bakhtar F., Zamri M.Y., On the performance of a cascade of improved turbine nozzle blades in nucleating steam - Part 3: Theoretical analysis, Proc. Inst. Mech. Eng. C J. Mech. Eng. Sci., 2011, 225, 1649–1671.

[6] Halama J., Fort J., Seifert M., Numerical solution of wet steam flow with a priori droplet size distribution, Proceedings of Conference on Topical Problems of Fluid Mechanics, Prague, 2010, 63–66.

[7] Schnerr G.H., Homogene Kondensation in stationaeren transsonischen Stroemungen durch Lavalduesen und um Profile, Habilitationsschrift, Fakultät für Maschinenbau, Universität Karlsruhe, 1986.

[8] Young J.B., Spontaneous condensation of steam in supersonic nozzles. Physicochem. Hydrodyn., 1982, 3, 57–82.

[9] Frenkel J., Kinetic Theory of Liquids., Oxford University Press, New York, 1946.

[10] Gyarmathy G., Grundlagen einer Theorie der Nassdampfturbine, Dissertation, Juris Verlag, Zürich, 1960.

[11] Dykas S., Wróblewski W., Łukowicz H., Prediction of losses in the flow through the last stage of low-pressure steam turbine, Int. J. Numer. Meth. Fluids., 2007, 53(6), 933–945.

[12] Dykas S., Wróblewski W., Two-fluid model for prediction of wet steam transonic flow, Int. J. Heat. Mass. Tran., 2013, 60, 88–94.

[13] Smołka K., Strozik M., Majkut M., Dykas S., Możliwości badań eksperymentalnych przepływu pary mokrej w układzie minisiłowni kondensacyjnej, Prace Naukowe. Konferencje, z. 27, Oficyna Wydawnicza Politechniki Warszawskiej, 2011, 233–240.

[14] Wróblewski W., Dykas S., Gepert A., Steam Condensing Flow in Turbine Channels, Int. J. Multiphas. Flow, 2009, 35(6), 498–506.

[15] Dykas S., Majkut M., Smołka K., Strozik M., Experimental research on wet steam flow with shock wave, Exp. Heat Transfer, 2015, 28(5), 417–429.

[16] Doerffer P., Dykas S., Numerical analysis of shock induced separation delay by air humidity, Int. J. Therm. Sci., 2005, 14(2), 120–125.