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SEPARATION OF THE LIQUID PHASE FROM THE STATOR BLADES OF THE LAST STAGE OF A 1000MW STEAM TURBINE

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Abstract: *The paper describes measurements of water film separation from the surfaces of hollow stator blades in the last stage of a large steam turbine for a nuclear power plant. Results are presented of the separation of the liquid phase, the efficiency of suction and the distribution of pressure at selected locations in the last stage during starting-up of the turbine. Attention is also paid to water extraction from the casing end wall. The main purpose of the paper is to find the efficiency of the water film separation and to provide general information about the wet steam flow in the last stage of the 1000 MW turbine.*

Keywords: ***Steam turbine, water film separation, experimental measurement.***

1. Introduction

The steam expansion in the low pressure (LP) stages of steam turbines is always terminated in the wet steam region. The liquid phase deposits on the blade surfaces creating water films that disintegrate at the trailing edges and form coarse droplets. In the case of a substantial circumferential rotor blade speed and increased exit wetness, extreme erosion damage can occur to the leading edges of the rotor blades. The operational reliability and service life of the blades should therefore be improved by extracting the water films from the surfaces of the stator blades. A number of experiments have already been conducted in laboratory conditions by Dejc et al. (1987) and Filippov et al. (1980). There are also the works of Tanuma et al. (1991) and Sakamoto et al. (1992).

Extensive experimental verification of the efficiency of suction removal of the liquid phase has been conducted by the present authors on a nuclear power plant 1000 MW turbine. In this case the liquid phase was exhausted together with the steam phase, which thus supported the transport of water. The exhausted steam was routed to the chamber above the rotor blade and the steam was then injected into the boundary layer on the wall of the diffuser in the exhaust hood. In this way, separation of the steam flow from the diffuser wall was prevented and its efficiency was improved.

2. Experimental facility and instrumentation

The meridional section of the last stage and the outlet diffuser is shown in Fig. 1. Pressure taps are placed at selected locations for pressure measurement. The pressure measurements were located on the left and right side of the turbine. The following values were monitored – total pressure at inlet to the last stage p_{00} measured at the leading edge of the nozzle, static pressures in the gap between the stator and rotor p_{1h} and p_{1t} and pressures p_{2h} and p_{2t} downstream of the stage. Pressure p_{ch} in the diffuser chamber is also important. Two blades for measuring of extracted water in the lower part of the turbine were separately connected directly to the pressure in the condenser. The water/steam mixture from these two blades did not go out through the diffuser chamber. The mean pressure on the blade surface at the slot locations p_{sb} was measured and, in the case of extraction, also the pressure inside the blades p_{hb}. Pressure p_{ch} is already critical with respect to the pressure p_{sb} in the case of the two instrumented blades. Thus, it was not necessary to measure the pressure in the other blades.

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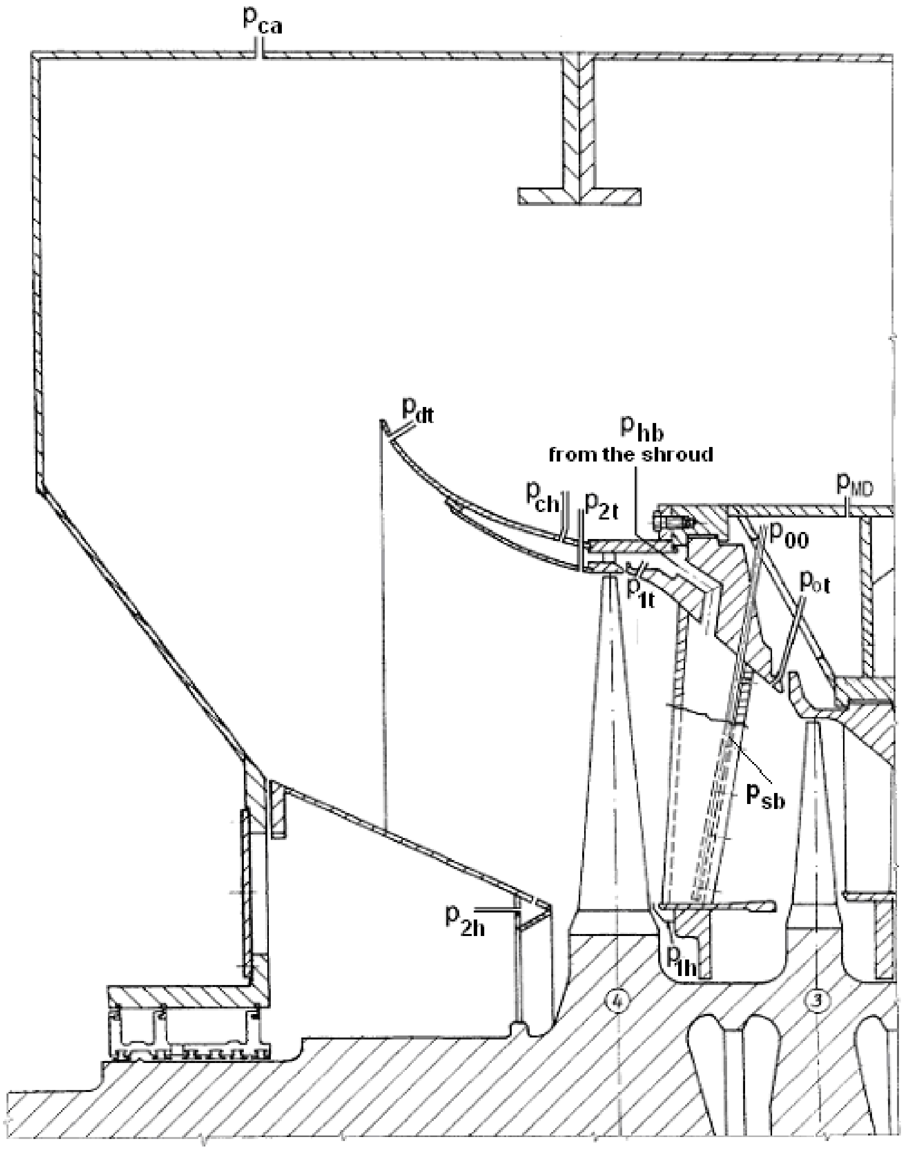

Fig. 1: Meridional section of the last stage and diffuser.

The water removed from both measured blades is routed to the measuring line. A diagram is shown in Fig. 2.

The extraction slots are located on the pressure and suction surfaces of the blade. All slots are 2 mm wide and they are perpendicular to the blade surface. The pressure is the same at all slots. The slots cover 1/3 of the length of the blade from the top wall.

It is assumed that the water in the hollow blades has a low velocity and flows down freely onto the surface of the tube connected to the tested blade. Through the drainage piping the water is routed to tank No. 1 where the volume of condensate collected in a given time is measured in order to obtain G_{v1} the mass flow rate. The remaining steam is routed to a centrifugal separator where most of the liquid phase is separated. It is caught and measured in tank No. 2. The actual centrifugal separator and a substantial part of the drainage piping are placed in the area of the exhaust hood and the upper part of the condenser. This ensures a stable temperature in the environment of the majority of the measuring system. The sections outside the condenser are insulated. The measuring line may be disconnected using valves. In order to prevent the piping from filling with water when measuring, the tested blade is permanently connected via a by-pass line to the low pressure in the condenser. The by-pass is closed when taking measurements.

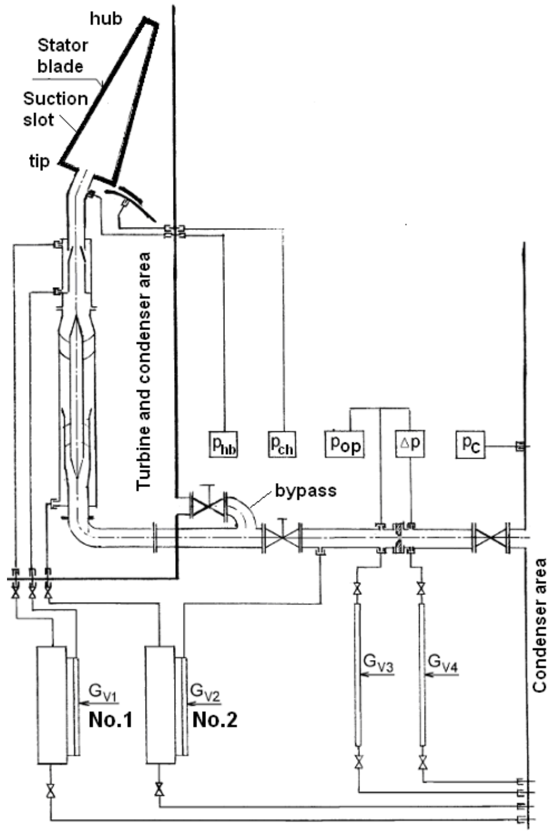

Fig. 2: Diagram of the water film separation from the surface of the hollow stator blade.

A similar piece of equipment is used to measure the amount of water moving on the surface of the shroud. A diagram of the measuring system is shown in Fig. 3. A groove is inserted in the extraction slot to draw off the steam-water mixture to a simple cyclone separator. It is assumed that the water film and large water drops are separated from the steam. The separated water is collected in a vessel in order to obtain G_{v5} the mass flow rate.

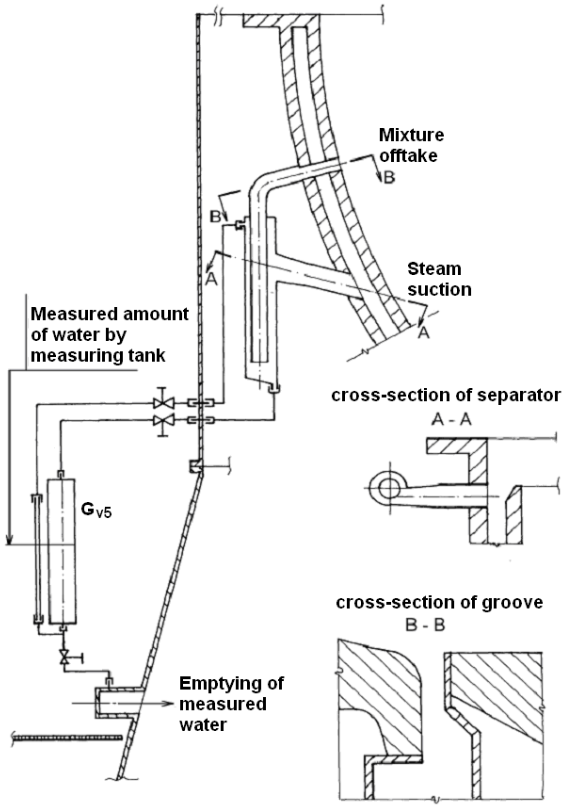

Fig. 3: Diagram of water draining from the shroud wall between the stator and the rotor shroud wall

3. Amount of water on the surface of the hollow blades

The measurement of the mass flow rate of the removed water was carried out from start up of the steam turbine running at idle to the full rated output. Full information about the water film deposited on the surfaces of the stationary blades was recorded. As shown in Fig. 2, the exhausted water is simultaneously collected in two measuring tanks (amounts G_{v1} and G_{v2}). At the same time, the presence of water upstream of the orifice plate is checked using a measuring cylinder to record the volume of caught water G_{v3}. In fact, no water was detected upstream of the orifice for any mode of operation. This confirms the good efficiency of the separator and insulation on the measuring line.

The suction of steam and water through the blade slots is a throttling process to a lower pressure. This means that the actual steam wetness at the place of extraction will differ from the measured value. It is therefore necessary to convert the measured conditions to the extraction. It is also true that the pressure inside the blade with extraction is lower than the pressure in the other blades. The blade with extraction is connected via the separator to the condenser. The pressure in the other blades is restricted to the pressure in the chamber from which steam is injected into the boundary layer on the diffuser wall. If steam is not exhausted via the slots, the mean pressure psb is measured at the place of extraction on the blade and $p_{sb} = p_{hb}$. The pressure drop at varying turbine power output is shown in Fig. 4.

Let psb be the pressure on the blade at the extraction slot location. Pressure p_{hb} is the pressure inside the hollow blade during extraction (i.e., at the time of the experiment). Inside other blades, the pressure is at the same level as pressure p_{ch} – pressure loss in drainage between the hollow blade and the chamber is neglected. The water film extraction was designed on the assumption that there would be a critical pressure difference across the slots. It is established that pressure pch corresponds to the critical pressure pcr, related to p_{sb}. There is a smaller pressure on the instrumented blades, which means that no greater amount of steam may enter the cavity of the blade. If there is water on the surface of the blade then it is removed with the accelerated steam phase to the cavity of the blade. The actual wetness of the extracted steam may therefore be greater than the wetness of the flow of steam close to the surface. In order to be able to estimate the efficiency of separation of the liquid phase, it is necessary to know at least the theoretical wetness of the steam at the location of the slots.

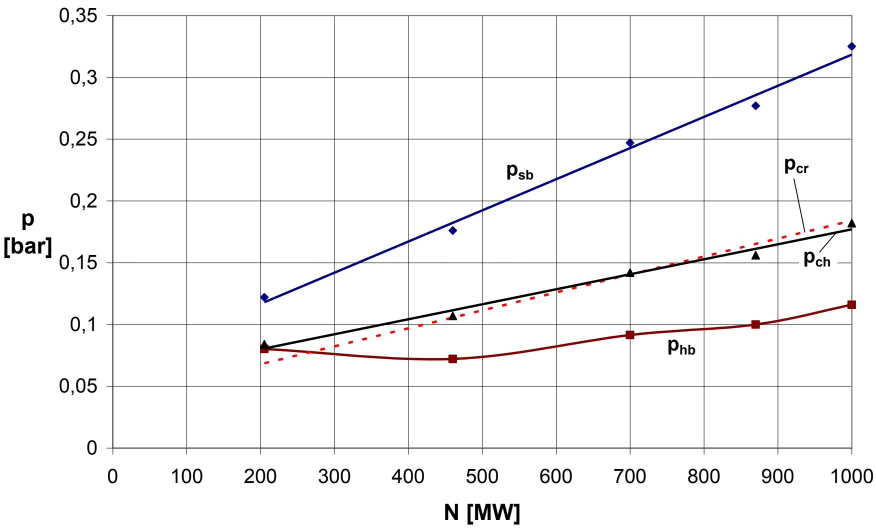

Fig. 4: Pressure values on the blade when extracting the water film.

The pressure conditions at the outlet from the stator are shown in Fig. 5. Due to the varying stage of reaction there is a greater pressure p_{1t} at the tip than at the hub p_{1h}. As the slots are located near the tip it is obvious that the pressure varies over the length of the slot. When calculating the efficiency of suction, we consider the mean pressure after the stator blade for the section of a blade with slot pressure p_{1s}. The mean wetness of steam downstream of the stator blade y_{1s} and the steam wetness at the slot location y_{sb} correspond to this pressure. The dependence of steam wetness on the turbine power output is shown in Fig. 6.

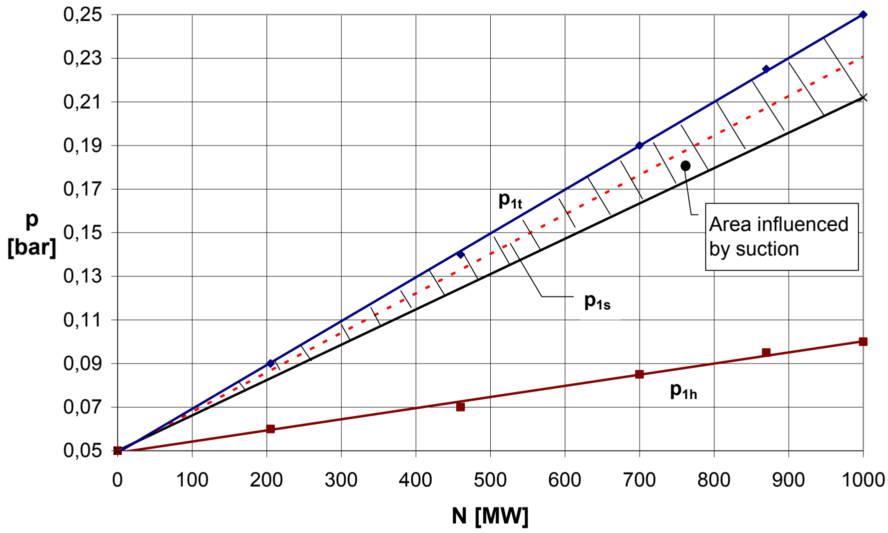

Fig. 5: Pressure conditions after the stator blade of the last stage.

The actual mass flow rates of the separated liquid phase from one blade are shown in Fig. 7. The extraction of water is apparent even for a power output of 150 MW. It is evident that the mass flow rates of exhausted water follow a linear characteristic; they are proportional to the overall mass flow rate of steam and the terminal wetness on the expansion line. The total amount of exhausted water is therefore higher in the overall number of blades. The record in Fig. 7 shows that the largest quantity of water was extracted by means of the centrifugal separator. Only one quarter of this amount is present on the surface of the piping (i.e., the mass flow rate G_{v1}). Total mass flow rate of separated water is given simply as $G_{vm} = G_{v1} + G_{v2}$.

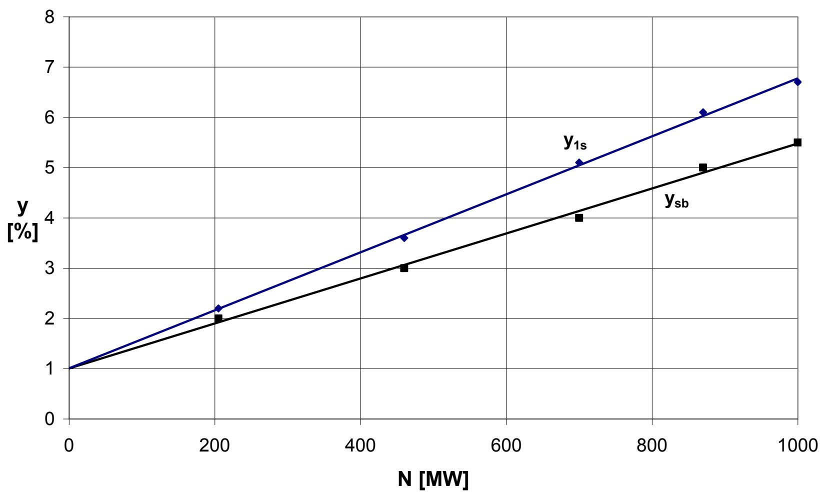

Fig. 6: Variation of mean steam wetness on the stator blade at the location of the slots.

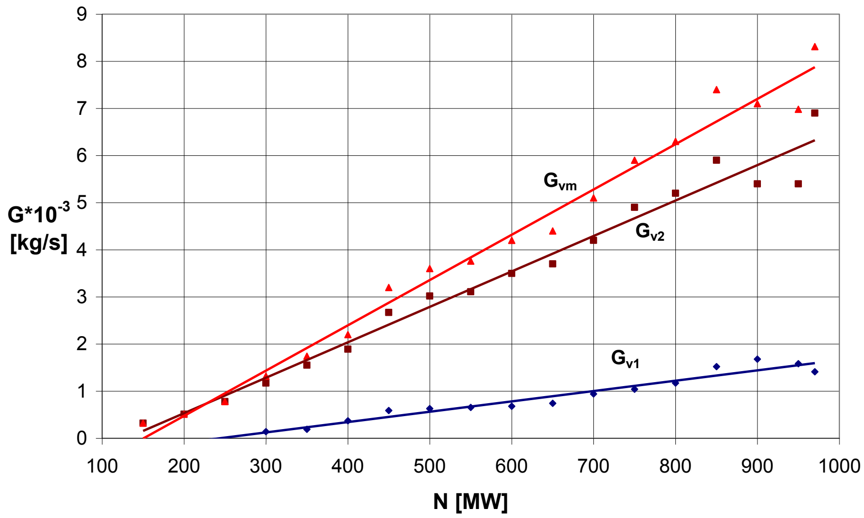

Fig. 7: Mass flow rate of separated liquid.

To establish the suction efficiency it is necessary to have at least an approximate idea of the mass flow rate of steam in the last stage at various power output levels of the turbine. Fig. 8 shows the increase of mass flow rate from the hub to the tip of the rotor blade according to calculations for the designed output of 1000 MW.

A steam mass flow rate of 62 kg/s flows through the section with slots at output of 1000MW. Fig. 9 shows the theoretical variation of mass flow rate with turbine power output. It also shows liquid phase mass flow rate G_{vt} corresponding to the theoretical mean wetness y_{sb} at the location of the slots. It is impossible to establish by experiment the actual distribution of water mass flow rate over the stator blade of the last stage, although an approximate distribution may be obtained using a numerical simulation. Based on such calculations, it may be inferred that substantial redistribution of the flow does not occur except on the rotor blade where the centrifugal forces act. Also backflow can occur in the vicinity of the hub of the last stage during reduced output. This was confirmed by measuring of the velocity field after the last stage.

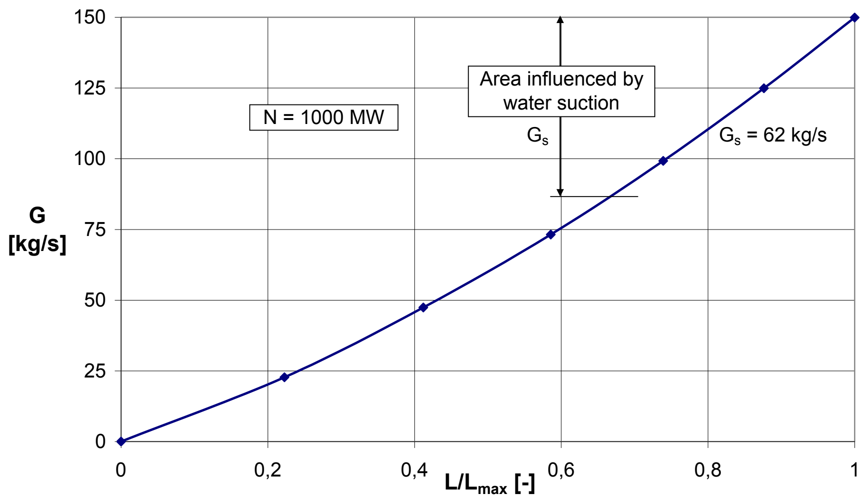

Fig. 8: Mass flow rate through the last stage for a turbine power output of 1000 MW.

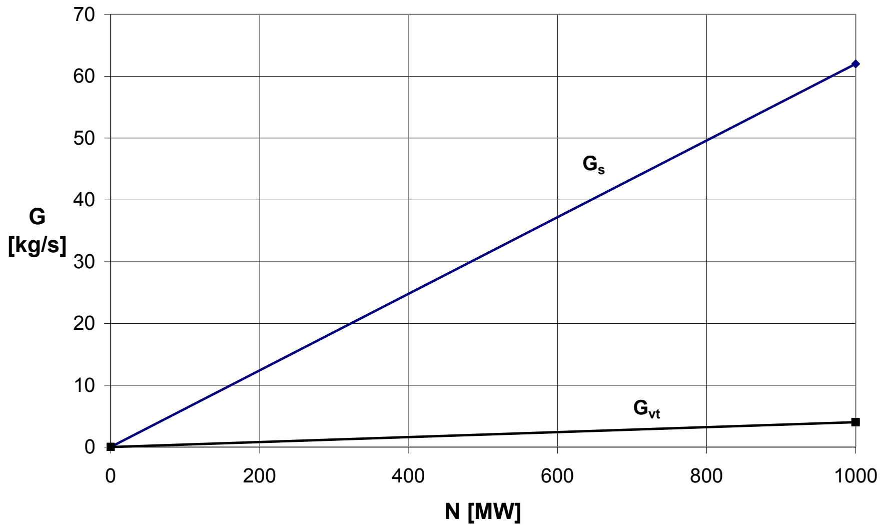

Fig. 9: Mass flow rate of steam through the stage with slots.

Changes of steam conditions on the blade slot are shown in Fig. 10. The external steam wetness y_{sb} changes to y_t after throttling to the internal pressure p_{hb} but the measured water mass flow rate G_{vm} corresponds to wetness y_m. By reverse conversion to the conditions at pressure p_{sb} we obtain the water mass flow rate G_{vsm} and wetness y_{sm}. We always consider the theoretical maximum steam mass flow rate G_{max} corresponding to wetness y_{sb}. The mass flow rate of water in the form of coarse droplets G_F is given by $G_F = G_{vsm} – G_{vs}$. The efficiency of water removal is given by $\eta_s = G_{vsm}/G_{vt}$ where G_{vt} is the theoretical mass flow rate of the liquid phase in the rotor passage at the slot location. The extraction efficiency η_F represents the share of the water film in the removed sample. The coefficient of liquid phase concentration k_{sb} represents the actual measured wetness divided by the theoretical one. An overview of these parameters is given in Table 1 and the steam wetness at the slots is shown in Fig. 11.

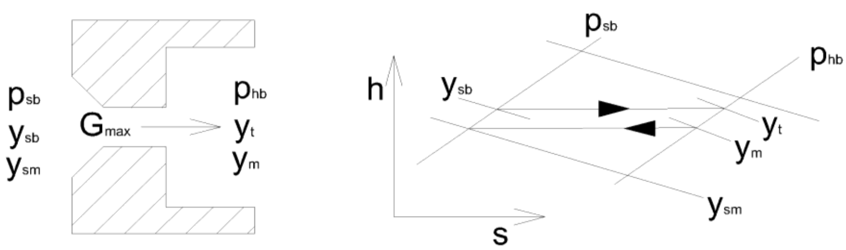

Fig. 10: Changes of pressure and wetness on the blade.

Tab. 1: Data related to the water extraction from the last stage.

N	MW	205	460	730	870	1006	Turbine power output
G_{max}	kg/s	0.0195	0.0304	0.0425	0.0479	0.056	Maximum steam mass flow rate through slots
y_{sb}	-	0.02	0.03	0.04	0.05	0.055	Theoretical wetness of steam at slots
G_{vs}	kg/s	0.00039	0.000912	0.0017	0.00239	0.00308	Theoretical water mass flow rate at slot, $G_{vs} = G_{max}\cdot y_{sb}$
y_t	kg/s	0.008	0.015	0.022	0.035	0.038	Theoretical wetness of steam inside the blades
G_{vm}	kg/s	0.0004	0.00287	0.0051	0.00705	0.00845	Mass flow rate of extracted water

G_{vsm}	kg/s	0.000509	0.00328	0.00602	0.0074	0.00966	Water mass flow rate of water at the slot location
y_{sm}	-	0.024	0.1	0.129	0.139	0.155	Steam wetness at the slot obtained from measurements
G_F	kg/s	0.00012	0.00237	0.00432	0.00501	0.00658	Theoretical coarse water mass flow rate, $G_F = G_{vsm} \cdot G_{vs}$
G_{vt}	kg/s	0.0065	0.0229	0.0498	0.0739	0.0944	Liquid mass flow rate in the top 1/3 of the blade channel
y_F	-	0.0061	0.0779	0.1016	0.1046	0.1175	Wetness of coarse dispersion $y_F = (G_{vsm} - G_{vs}) / G_{max}$
η_s	-	0.078	0.143	0.12	0.10	0.102	Water removal efficiency $\eta_s = G_{vsm}/G_{vt}$
η_F	-	0.254	0.779	0.787	0.752	0.758	Efficiency of suction of water film, $\eta_F = y_F/y_{sm}$
k_{sb}	-	1.2	3.33	3.22	2.78	2.82	Coefficient of liquid phase concentration, $k_{sb} = y_{sm}/y_{sb}$

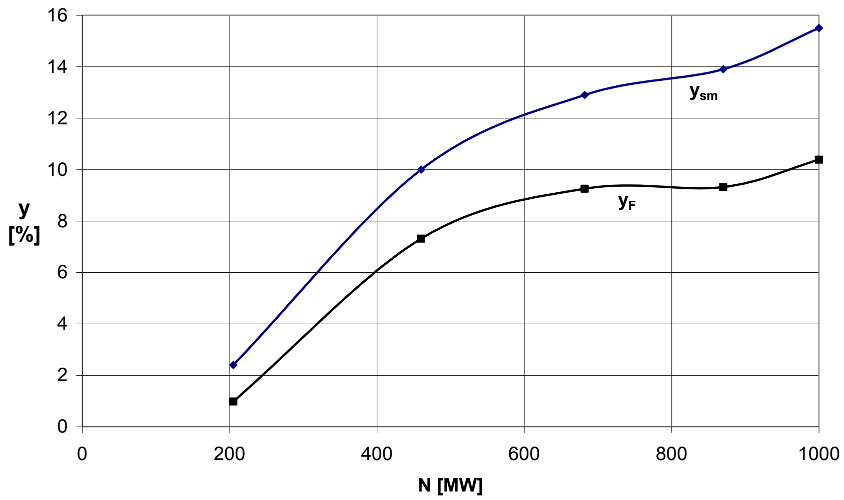

Fig. 11: Steam wetness at the slots.

The water phase separation starts to be more effective from an output of 400 MW. The water removal efficiency is shown in Fig. 12 where it can be seen that it rises to a level of about 10%. The results correspond to other available information by Dejc et al. (1987) and Tanuma et al. (1991). Thanks to the water film separation, the steam is drier by about 10% for all wetness levels in the main flow in the upper third of the whole length of the stator blade channel. About 70% of the separated water fraction corresponds to the water films on the blade surfaces.

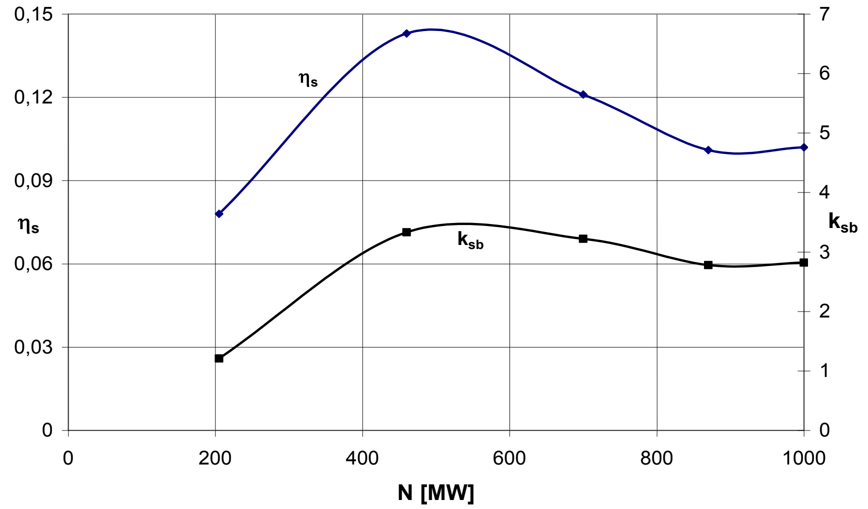

Fig. 12: Efficiency of water film separation.

4. The liquid phase on the casing end wall

Water reaches the shroud of the stage mainly due to the centrifugal force, which affects the water film on the rotor blades of the penultimate stage. Also, large water droplets move towards the shroud due to inertia and a substantial circumferential component of velocity downstream of the stator blade. The groove upstream of the rotor blade of the last stage is to allow suction of the water film formed in this way and thus provide better protection of the tip region of the rotor blades. An experiment was conducted to measure the amount of water moving onto the casing. A diagram of the measuring system is given in Fig. 3. The results of the experiments are presented in Fig. 13.

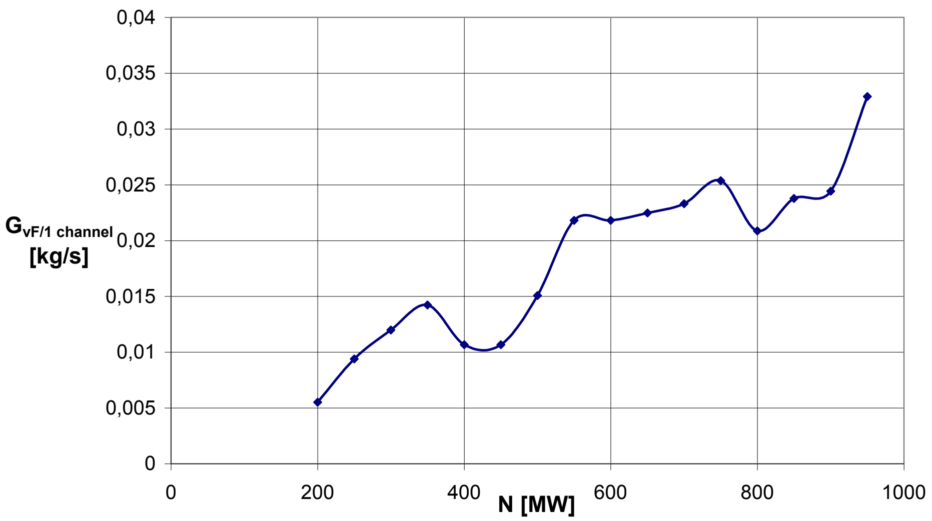

Fig. 13: Mass flow rate of water extracted from the casing.

The diagram shows the mass flow rate of water on the wall G_{vF} corresponding to one pitch between the stator blades. The quantity of liquid extracted from the casing surface was greater than that collected from the surface of the stator blades through the slots (mass flow rate G_{vsm}) by a factor of 3.6. The water that has not been removed upstream of the last stage reaches the wall. It is assumed that there is a uniform distribution of the liquid phase along the whole circumference. The water extracted on the section 3 cm long is scaled up to the whole circumference and also to 1 pitch of the stator blades. It is assumed that the efficiency of separation of the steam and liquid phases in the separator is 100%.

5. Distribution of steam wetness after the last stage

It is important to know the real wetness distribution after the last stage of the turbine. The removal of part of the liquid phase from the main flow results in distortion of the final wetness. Changes to the steam expansion occur that affect the efficiency of the LP stages. An approximation of the distribution of the steam wetness downstream of the last stage may be obtained from the measurements made by the Czech Technical University in Prague using an optical probe. The results of the measurements are given in Fig. 14. Further data, including the mean value of steam wetness, are given in Table 2.

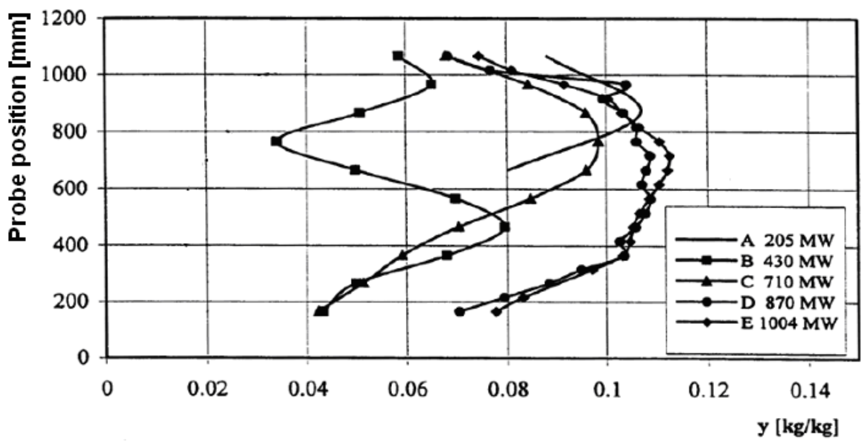

Fig. 14: Distribution of steam wetness after the last turbine stage.

Tab. 2: Steam parameters in the LP stages of the turbine at 1000 MW.

Measurement		C	D	E
Power output P_N	MW	710	870	1004
Pressure before LP	MPa	0.523	0.616	0.690
Temperature before LP	°C	253.8	251.2	248.5
Pressure after LP (hub)	kPa	7.87	7.06	7.82
Pressure after LP (tip)	kPa	7.17	6.22	6.67
Mean wetness after LP	kg/kg	0.0777	0.0966	0.1000

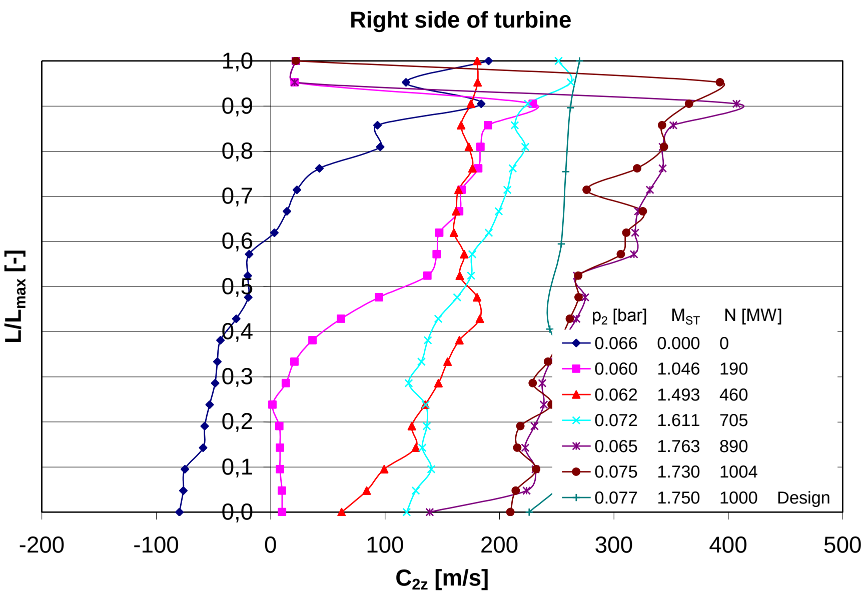

Fig. 15: Axial velocity component after the last stage.

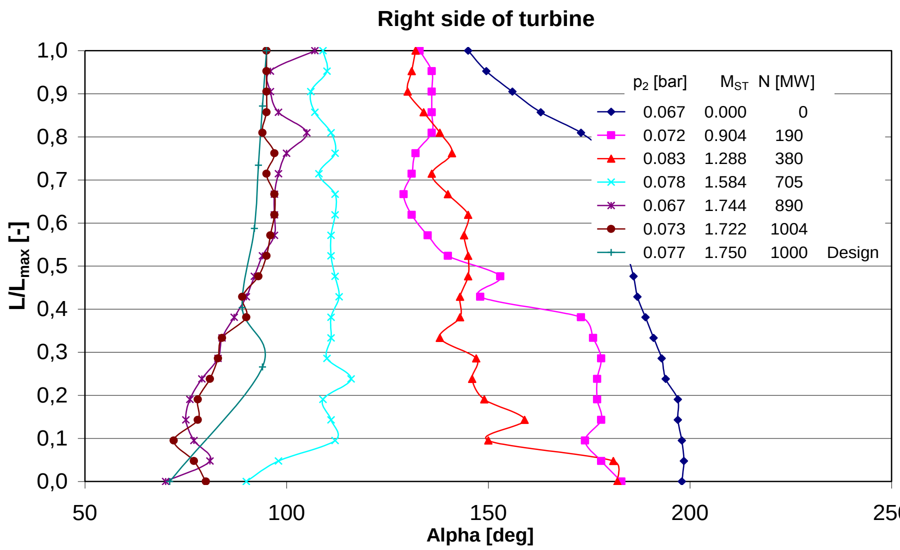

Fig. 16: Outlet angle of the flow from the last stage.

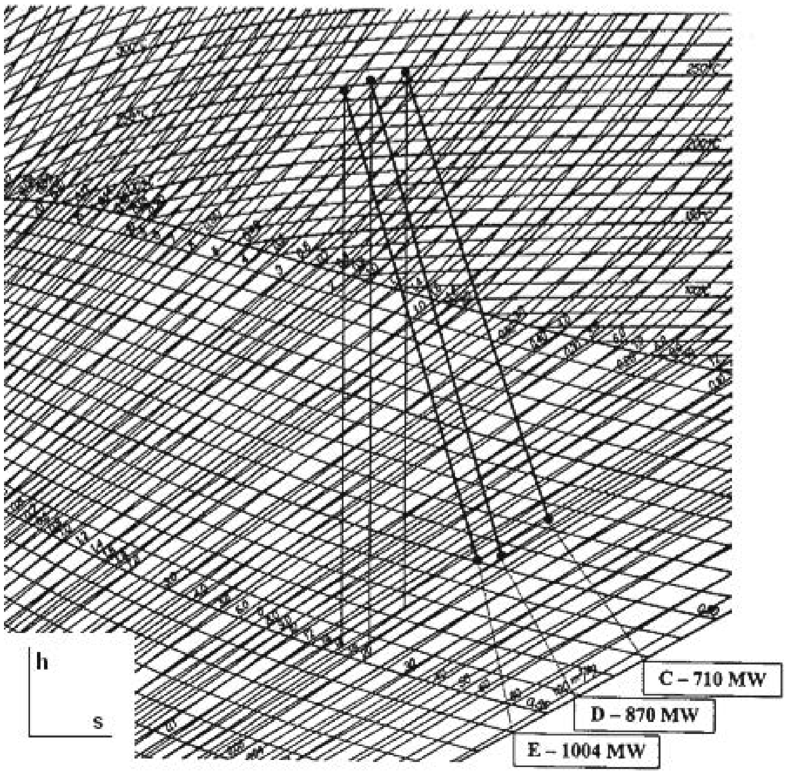

Fig. 17: Expansion lines in the LP stages of the turbine at 1000 MW load.

The variation over the blade height of the axial component of velocity at the outlet from the last stage measured by a 7-hole probe is shown in Fig. 15. It can be seen that backflow was present over the lower half of the blade up to an output of about 200 MW. As the turbine load changes, so also does the output angle of flow from the last stage as shown in Fig. 16.

The wetness drop by the top part of the stage was observed. The expansion line in the LP stages of the steam turbine and the line obtained with the help of the measured data are marked in Fig. 17. Three power output levels are shown. The changes in the individual stages are not considered.

6. Conclusions

Water separation slots support the extraction of the water film from the surface of hollow blades; about 70% of the removed water comes from the water film. The overall efficiency of water separation is about 10%.

Extraction of the water films is possible in all operational modes of the turbine. The extraction of the water film should contribute to reduced erosion wear of the leading edges of the rotor blades in the last stage.

The mass flow rate of water moving on the casing surface corresponds to $0.37 \cdot G_{vt}$ where G_{vt} is the total mass flow rate of water in the rotor passage at the location of the slots.

The pressure conditions in the last stage are effective for water extraction at all operational modes of the turbine.

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