

Turbine Steam, Chemistry and Corrosion

Generation of Early Liquid Films in Turbines

TR-113090

Final Report, September 1999

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CITATIONS

This report was prepared by

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This report describes research sponsored by EPRI .

The report is a corporate document that should be cited in the literature in the following manner:

Turbine Steam, Chemistry and Corrosion: Generation of Early Liquid Films in Turbines, EPRI,
Palo Alto, CA: 1999. TR-113090.

REPORT SUMMARY

Steam turbines have experienced decades of corrosion and deposit buildup. Most outage hours are due to corrosion of low-pressure blades in the phase transition zone (PTZ). This report provides comprehensive information on the properties of the liquid films that form on turbine surfaces in the PTZ

Background

Researchers have been studying effects of impurities in steam since the 1930s. Two earlier EPRI reports (TR-108184 and TR-108185) provided information on the physico-chemical phenomena involved in impurity concentration and condensation in the PTZ. To improve the understanding, detailed further measurements were needed to characterize the liquid films.

Objective

To conduct measurements of liquid films on a model turbine using a broad range of water and steam chemistries with controlled additions of impurities to the steam.

Approach

The project team prepared the model turbine for testing by installing specially designed instrumentation to measure the thickness and composition of liquid films forming on blade surfaces and the temperature and pressure of the steam, liquid films, and blades. The investigators tested eight different combinations of chemistries based on phosphate treatment and oxygenated treatment with various levels of sulfate and chloride impurities.

Results

The report contains very detailed information on all aspects of liquid films as a function of the inlet steam composition, temperature, and pressure. Key findings include the following:

- The concentration of corrosive impurities in the liquid films can be up to an order of magnitude higher than in the early condensate droplets.
- Phosphate chemistry (pH 9.2) produces the highest concentration of corrosive impurities and oxygenated treatment (pH 8.2) the lowest.
- Oxygen does not concentrate in the liquid films. However, liquid films are reduced in thickness; and maximum supercooling occurs when oxygen is added to steam.
- An elevated sulfate in the turbine inlet stream results in increased contamination of the early condensate and the liquid films with chloride.

- The pH of the early condensate and the liquid films is about 2-3 pH units lower than the pH of the turbine inlet steam.

EPRI Perspective

This work is part of a much larger effort to quantify the PTZ of fossil and nuclear turbines. Because field monitoring conducted subsequent to this work indicated that the two-phase media flowing from the PTZ are charged, further studies have been initiated on the model turbine. These will measure the charge and electrochemical potential of the liquid films as a function of steam composition.

EPRI has started to use all this information in two follow-on activities: a) to develop a software code to assess the corrosion fatigue and stress corrosion cracking potential for blades and disks, and b) to modify the charged media by application of high voltage electric fields or through surface tension.

TR113090

Keywords

Power Plant Availability

Steam turbines

Steam Chemistry

Corrosion

Moisture

Deposits

ABSTRACT

This report contains the results of a study of the effect of different chemistries with controlled additions of impurities on the formation of liquid films on turbine surfaces, and the concentration of impurities in the liquid films. The information presented is based on experimental results produced on the model turbine with an attached test channel at the Moscow Power Institute, Russia. The objectives were to collect data from the model experimental turbine which was supplied with two of the predominant steam chemistries used in the utility industry worldwide. The work represents the second phase of the EPRI project on “Turbine Steam, Chemistry, and Corrosion: Experimental Turbine Tests,” which was originally initiated in conjunction with an international collaborative research program. The major purpose of this project was to gain additional knowledge and understanding of the real turbine environment in the Phase Transition Zone (PTZ).

The experimental results are presented as follows:

- *The test rigs and procedures, and the accuracy of measurement* are discussed in Chapter 2. The test equipment and procedures, including the test model turbine, wet-steam test rig, laser probe, early condensate and liquid film sampling system, and chemistry monitoring are described.
- *The experimental results* are discussed in Chapter 3. The influence of different chemistries with different levels of impurities on the concentration of impurities in the early condensate and liquid film, moisture, droplet size, and liquid film thickness/temperature are discussed.
- *The conclusions* are presented in Chapter 4.

One Appendix is included which provides the detailed test results. Table A-1 gives the data on inlet steam parameters (pressure and temperature), Table A-2—inlet steam chemistry; Table A-3—liquid film thickness along the test channel; Table A-4—fluid temperature on wall surface; Table A-5—temperature of wall surface; and Table A-6—static pressure along the test channel.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the special contributions to the project which are listed below:

- Kaluga Turbine Manufacturing Plant, for manufacturing and supplying hardware and instruments needed for turbine operation.
- Nauka Stock, for assembling and adjusting the turbine components.
- MEI Power Plant, for providing steam and maintaining the required feedwater and boiler water conditions during the tests.

The authors thank the following members of the MEI team who participated in the tests:

Dipl. Eng. R. Agapov
Dipl. Eng. V. Anan'ev
Dipl. Eng. O. Ermakov
Dipl. Eng. I. Gimadeeva
Dr. L. Kiselev
Dipl. Eng. L. Makarova
Dipl. Eng. K. Povarov
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Tech. P. Shemenev
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EXECUTIVE SUMMARY

This report contains the results of a study of the effect of different chemistries with controlled additions of impurities on the formation of liquid films on turbine surfaces, and on the concentration of impurities in the liquid films. Particular emphasis is placed on the concentration of impurities in, and the thickness and temperatures, of liquid films formed on metal surfaces in the phase transition zone. This is the second phase of the EPRI project on “Turbine Steam, Chemistry, and Corrosion: Experimental Turbine Tests” which was initiated in conjunction with an international collaborative research program.

Under the previous phase of the EPRI project the work was performed on the ET-3M test turbine at MEI to study the effect of different chemistries on the concentration of impurities in the early condensate, on early condensate droplet size and thickness of liquid films generated on the stationary blades.

The main conclusion was that, in spite of increases in the impurity content in the early condensate compared with steam, this was not considered harmful enough in terms of metal corrosion and cracking. It was suspected that higher levels of chloride and sulfate could be present in the liquid films generated on the blade surfaces.

The purpose of this phase of the project was to provide insight into the nature and composition of films on blade surfaces by performing tests with another model turbine with an attached test channel, using different water treatments with controlled additions of impurities.

From these tests, a much better quantitative understanding of the environment within the phase transition zone of steam turbines has been developed. This knowledge will be used to define the environments for supplemental testing of corrosion of turbine materials, to develop further the steam purity limits for operating fossil and nuclear turbines, and for incorporation of steam chemistry and corrosion into blade and disk design codes.

Analysis of the experimental results leads to the following conclusions:

- Concentration of corrosive impurities in the liquid films formed on the surface of blades and disks can be an order of magnitude higher than that in the EC.
- For the studied chemistries, an increase in the level of chloride and sulfate in the inlet steam resulted in an increase in the concentration of these impurities in the early condensate and the liquid films.

-
- Use of PT3.0 chemistry produces the highest concentration (and concentration ratio) of corrosive impurities, and the use of OT results in the lowest level (and concentration ratio) of chloride and sulfate in the early condensate and the liquid films.
 - An elevated sulfate in the turbine inlet steam results in increased contamination of the early condensate and the liquid films with chloride.
 - The pH of the early condensate and the liquid films is about 2 - 3 pH units lower than the pH of the turbine inlet steam.
 - Oxygen does not concentrate in the early condensate or the liquid films.
 - At constant turbine operating parameters (p_0 , T_0 , p_c , G , f), a change from PT3.0 to OT, and different initial levels of chloride and sulfate (about 2 - 70 ppb), does not result in a change in the size of the early condensate droplets generated during steam expansion in the turbine.
 - Increase in the steam moisture at the exit of the turbine from 0.5 to 4.0% results in an increase in droplet size (r_d) from 0.13 to 0.15 μm .
 - Maximum liquid film thickness is measured with PT3.0.
 - Decrease in ammonia level in the inlet steam results in a reduction of the liquid film thickness.
 - Feed of oxygen in to the steam with PT3.0 results in a reduction of the liquid film thickness.
 - At low levels of chloride and sulfate in the inlet steam (<10 ppb) with OT the maximum supercooling and maximum concentration ratio of impurities in the liquid film as compared to the early condensate are found.

Notation

The major notations used in this report are the following:

δ	Thickness (μm)
ϵ	Pressure drop through stage, p_2/p_0
d	Diameter (μm)
f	rpm
G	Mass flowrate (kg/s)
h	Enthalpy (kJ/kg)
n	Concentration ratio of impurities
p	Pressure (MPa, kPa, psi)
r	Radius (μm)
S	Entropy (kJ/(kg °C))
T	Temperature (°C, °F)
ΔT	Degree of superheat/supercooling (°C, °F)
x	Dryness (%)
y	Moisture content (%)
PT	Phosphate treatment
NA	Treatment with no additions
OT	Oxygenated treatment
EC	Early condensate
IS	Inlet steam
LF	Liquid film

Subscripts

0	Total inlet parameter of flow
1	Nozzle inlet parameter of flow
c	Condenser parameter
ch	Channel
d	Droplet
f	Film
s	Saturation
sh	Superheat

1

INTRODUCTION

Corrosion of low pressure steam turbine blades and disks due to stress corrosion cracking and corrosion fatigue, and the associated loss of efficiency and MW capacity remain as one of the most persistent problems in the fossil and nuclear utility industry⁽¹⁻⁴⁾.

Components of power generating units, which operate in the phase transition zone of the steam turbine are mostly subjected to an increased corrosion-erosion wear. Decrease in reliability and efficiency of these turbine stages is mostly due to corrosion processes, mainly as corrosion fatigue of rotating blades and corrosion cracking of IP and LP disks. Metal failure results from pitting corrosion and development of cracks initiating at pits. Generation of corrosive environments on the surfaces of the components in the phase transition zone is one of the basic reasons for initiation of corrosion pits⁽⁵⁻⁸⁾.

In the turbine flowpath, at the phase transition zone, early condensate (EC) nuclei with an increased level of impurities are formed. The EC droplets may precipitate on blade surface and form liquid films; they can evaporate during flow and form the highly concentrated salt solutions on turbine metal surfaces. The level of corrosive impurities in these films may be much higher than in the EC. These films can be formed and exist in superheated steam too. It is now clear that the generation of highly concentrated solutions on turbine metal surfaces is an important phenomenon, which can destroy protective surface layers.

Generation and existence of concentrated liquid films depends on the turbine operating conditions and the chemistry parameters, as well as the metal type and surface condition. These features have not been properly studied to date because of the complexity of these processes, the need to perform the studies on turbines with transient operating conditions, together with an ability to monitor EC at droplet diameters of less than 1 μm and liquid films up to about 150 μm .

In previous EPRI research, work was performed on the ET-3M test turbine at Moscow Power Institute (MEI) to study the effect of different chemistries on the concentration of impurities in the EC, on EC droplet size and thickness of liquid films generated on the stationary blades. It was shown that, in spite of increases in the impurity content in the EC compared with steam, this was not harmful in terms of corrosion cracking⁽⁹⁾.

Earlier data^(10, 11) showed that metal corrosion may develop if the concentration of corrosion impurities in solution is between 1-3%. The data on the amount of chloride and sulfate in the EC with different chemistries and inlet levels of the impurities from the first phase of this work are shown in Figures 1-1 and 1-2⁽⁹⁾, where it is clear that the concentrations of chloride and sulfate in the EC are much lower than 1-3% (i.e. that these EC droplets are not corrosive).

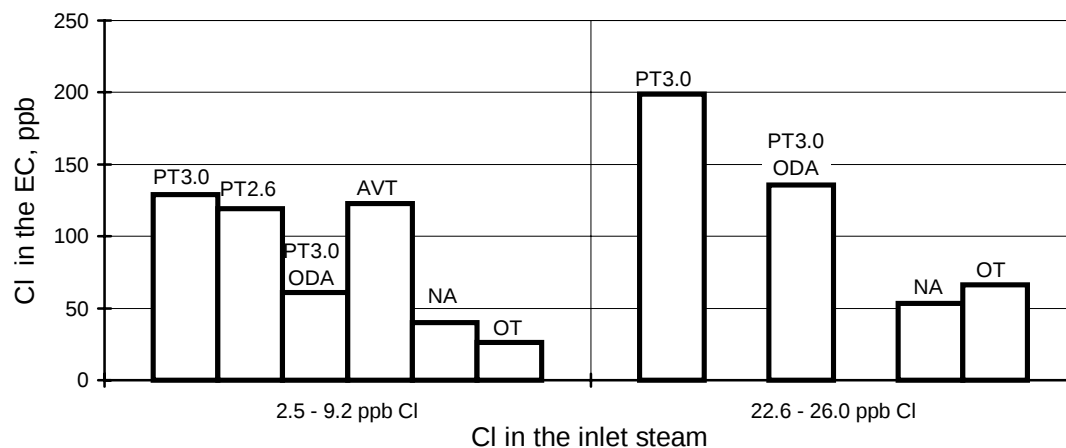
In the previous research the liquid film thicknesses were also measured on the stationary blade⁽⁹⁾. Similar measurements were performed earlier on the ET-12 test turbine⁽¹²⁾. Some of these results are shown in Figures 1-3 and 1-4.

The measurements of liquid film thickness on stationary and rotating blades with different steam parameters at the test cascade inlet (Figure 1-3) and on the surface of the disk and diaphragm (Figure 1-4) show that existence of liquid films is possible even at small inlet steam superheat ($\Delta T < 10\text{ }^{\circ}\text{C}$).

In those tests an attempt was made to sample liquid film from the stationary blade and to study the liquid film chemistry⁽¹³⁾. In spite of the significant complexity of liquid film sampling, data was produced which confirmed the possibility of concentration of impurities in liquid films up to corrosive levels. But these results did not account for the effect of composition and concentration of impurities in the turbine inlet steam, or for the type of cycle chemistry.

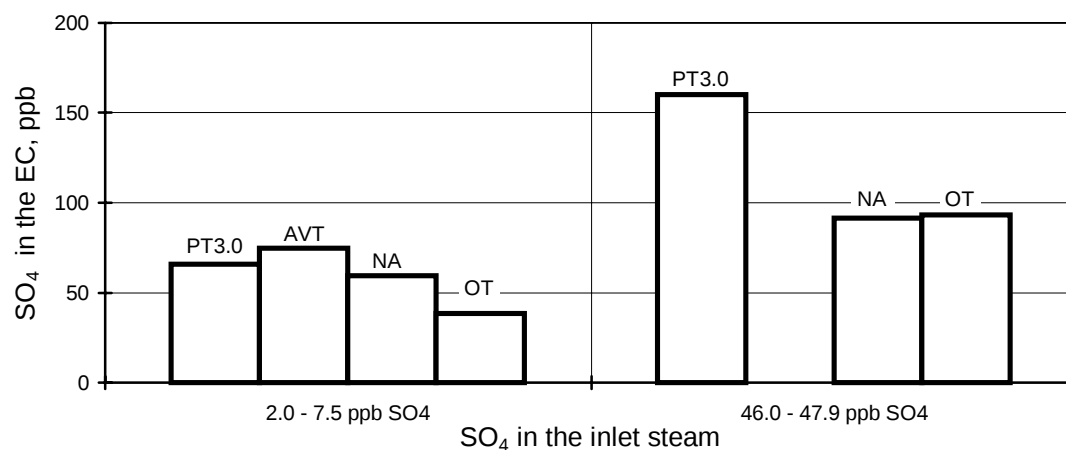
Therefore, the research in this current phase of the EPRI program was performed to study the process of generation of highly concentrated solutions in the phase transition zone of steam turbines. The main objectives of this research were to:

- Develop a test rig and system of measurement for the study of precipitation of fine droplets and the generation of liquid films.
- Study the effect of different chemistries – phosphate (PT) and oxygenated (OT) on the contamination of the liquid film with chloride and sulfate at different levels of these impurities in the turbine inlet steam.
- Study liquid film thickness and temperatures on metal surface with the above-mentioned chemistries and different levels of chloride and sulfate in the turbine inlet steam.



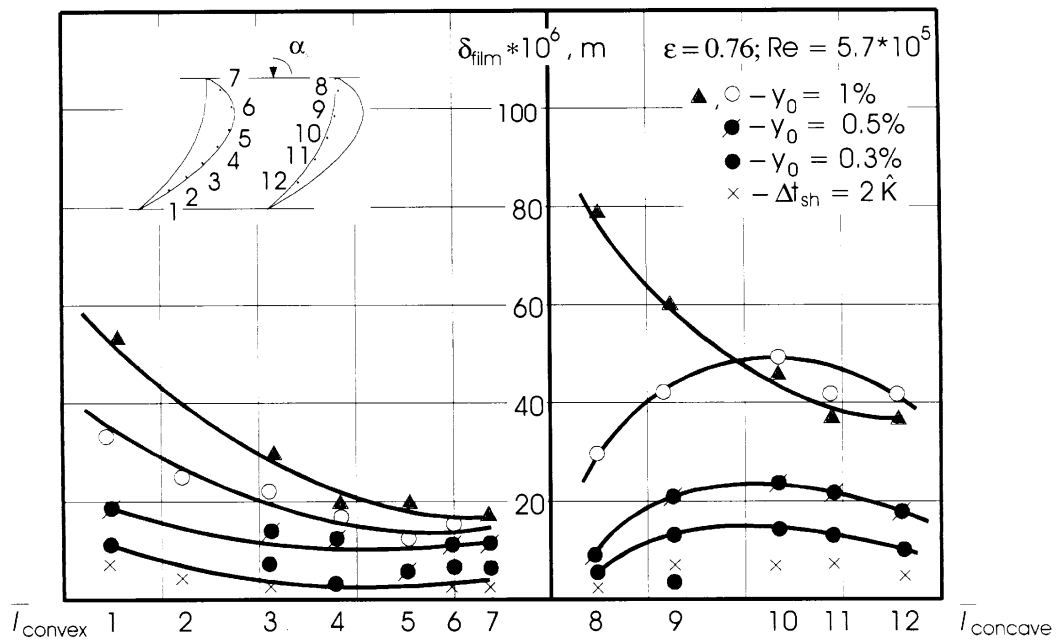
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Figure 1-1
Chloride Content in the Early Condensate (Middle Section of the Blade) with Different Chemistries for Two Chloride Levels in the Inlet Steam

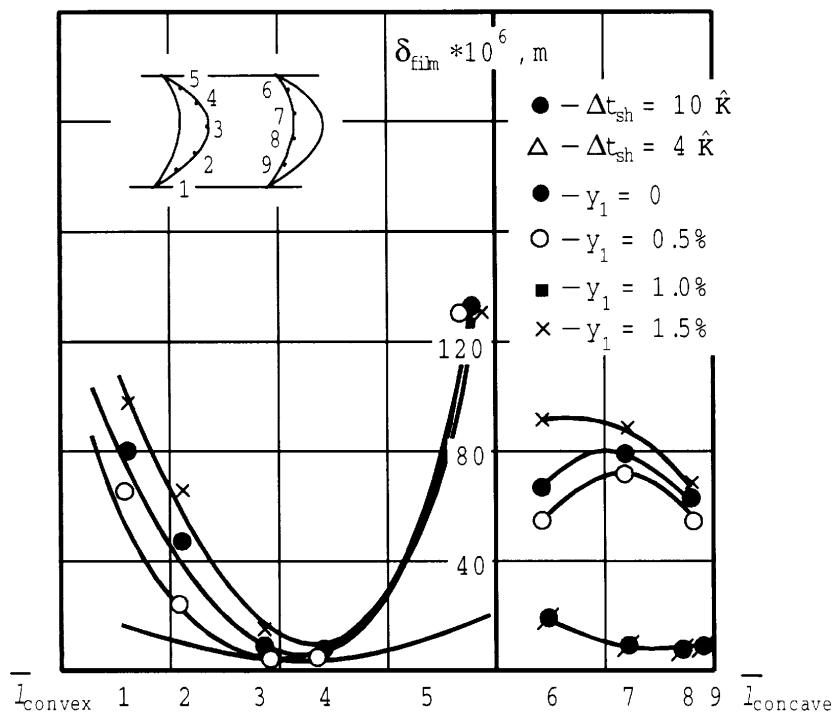


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Figure 1-2
Sulfate Content in the Early Condensate (Middle Section of the Blade) with Different Chemistries for Two Sulfate Levels in the Inlet Steam



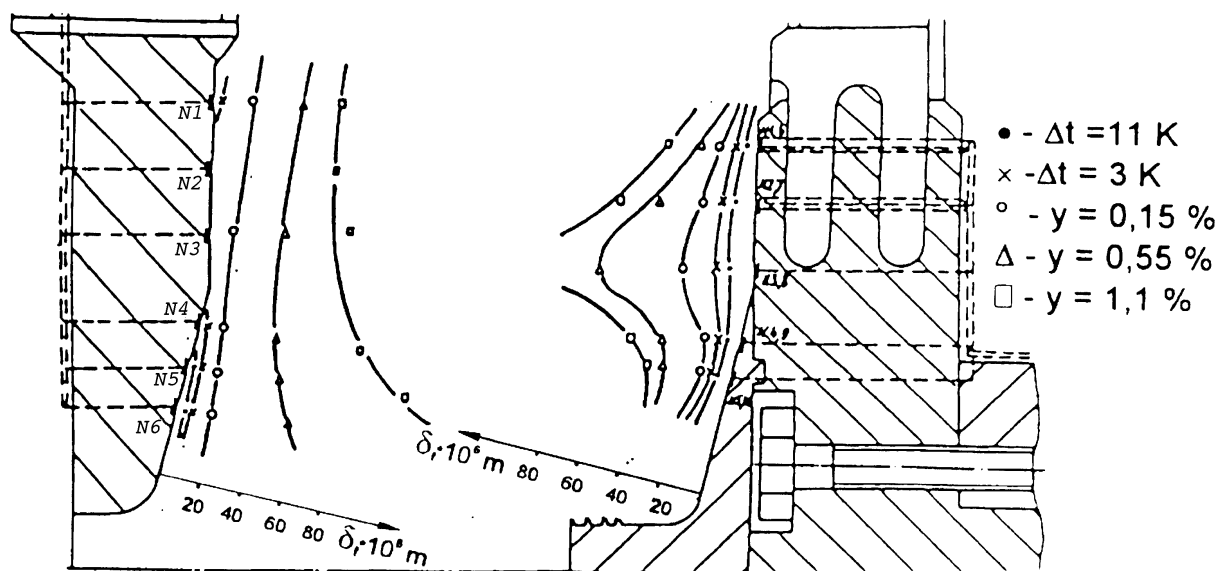
a)



b)

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Figure 1-3
Change of Liquid Film Thickness along the Profile of (a) Nozzle and (b) Rotating Cascades



Source: Reference 13

Figure 1-4
Liquid Film Thickness on Disk and Diaphragm of Turbine Stage

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2

TEST RIGS AND PROCEDURES: ACCURACY OF MEASUREMENT

ET-12 Test Turbine: Design, Cycle Diagram, and System of Measurement

The ET-12 test turbine was developed to study different parts of the wet-steam turbine flowpath. The turbine inlet steam allows for the following wide range of parameters to be studied: initial pressure $p_0 = 0.05 - 0.6$ MPa (7.3 – 87.1 psi), initial temperature $T_0 \leq 207$ °C (405 °F), initial moisture $y_0 = 0 - 20\%$, and condenser pressure $P_c = 0.02 - 0.1$ MPa (2.9 – 14.5 psi).

The longitudinal section of the test turbine is shown in Figure 2-1. The turbine case is a cylindrical shell reinforced with stiffening ribs. It has horizontal and vertical joints and consists of three parts: nozzle case with steam inlet (1), separable middle part (2), and exit part (3). Steam is supplied to the wet steam rig where the liquid film measurements are made (Test Channel, Figure 2-2) from the upper section of the exit part via port (4).

The rotating blades of the stages are attached to the independent shafts installed in special floating bushes (5 and 6), which absorb the axial and radial forces applied to the rotor.

In this study the test turbine had only one shaft. The shaft bushing (5) and the steam inlet (1) are installed on the fixed front turbine support (7). The exit part of the case (3) with the rear support (8) can move in the guides (9) of the bedplate (10) in the axial direction. In addition, the guides (9) allow for thermal expansion of the turbine case. The steam is exhausted via two branch pipes (11) located in the bottom section of the turbine case.

The turbine is loaded with the three-disk hydrobrake (12). Turbine rpm can be controlled over a wide range with change in supply and discharge of water passing through the hydrobrake chambers, and by disconnecting them.

The case of the hydrobrake is attached to the floating bushing. In the working condition the bushing along with the rotor and the hydrobrake floats up under the action of the oil supplied. Careful bushing assembly and adjustment eliminate dry friction completely between the floating structure and the fixed part of the bushing. The torque due to liquid friction in the floating bushing is insignificant. Therefore, the torque measured on the hydrobrake case includes the friction torque of the disk and friction torque in the bearings. This results in high accuracy of the torque produced by the turbine shaft.

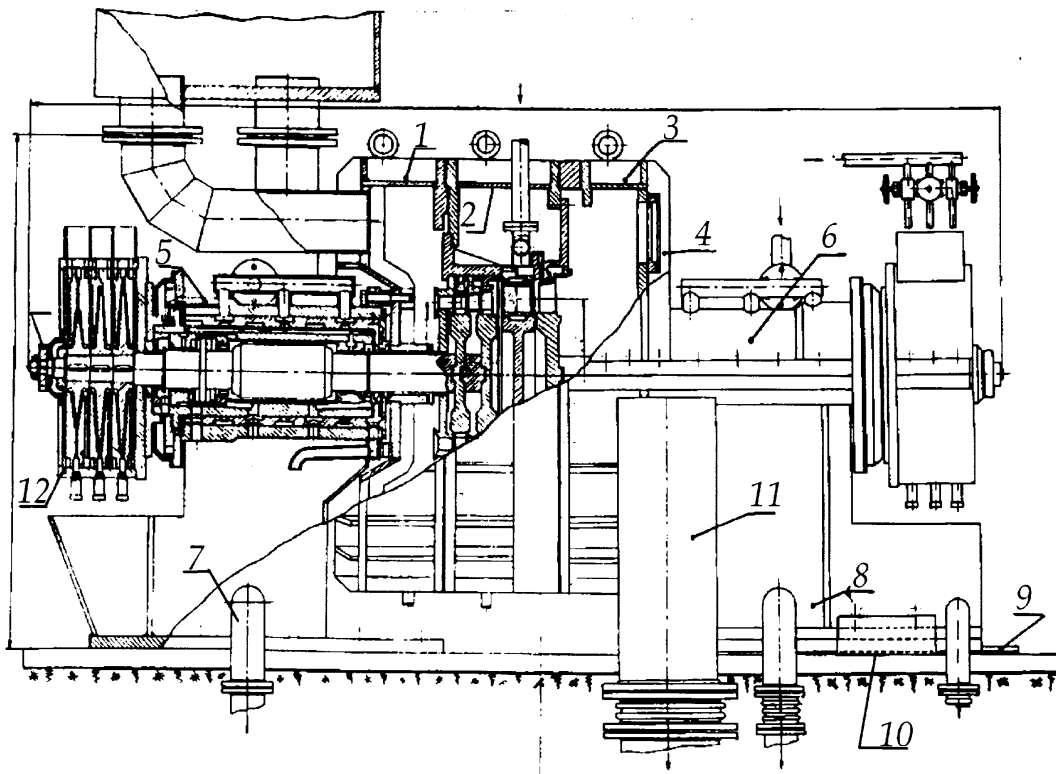


Figure 2-1
Longitudinal Section of the ET-12 Test Turbine

**1 – nozzle case with steam inlet; 2 – separable middle part; 3 – exit part; 4 – port;
5 and 6 -floating bushings; 7 – front turbine support; 8 – rear turbine support;
9 – guides; 10 – bedplate; 11 – branch pipe; 12 – hydrobrake**

The turbine has an electronic protection system, which includes: electronic digital overspeed governors to ensure maximum permissible rpm, protection against minimum pressure of water supplied to the hydrobrake, and protection against minimum pressure of oil supplied to the bearings.

Steam to the turbine is supplied by extraction from the MEI Power Plant turbine at pressure $p_{ex} = 0.6 \text{ MPa}$ (87.1 psi). On the way to the turbine, steam is throttled from point 1 (Figure 2-2) to the required pressure at point 2. Then it passes through a multi-stage attemperation system.

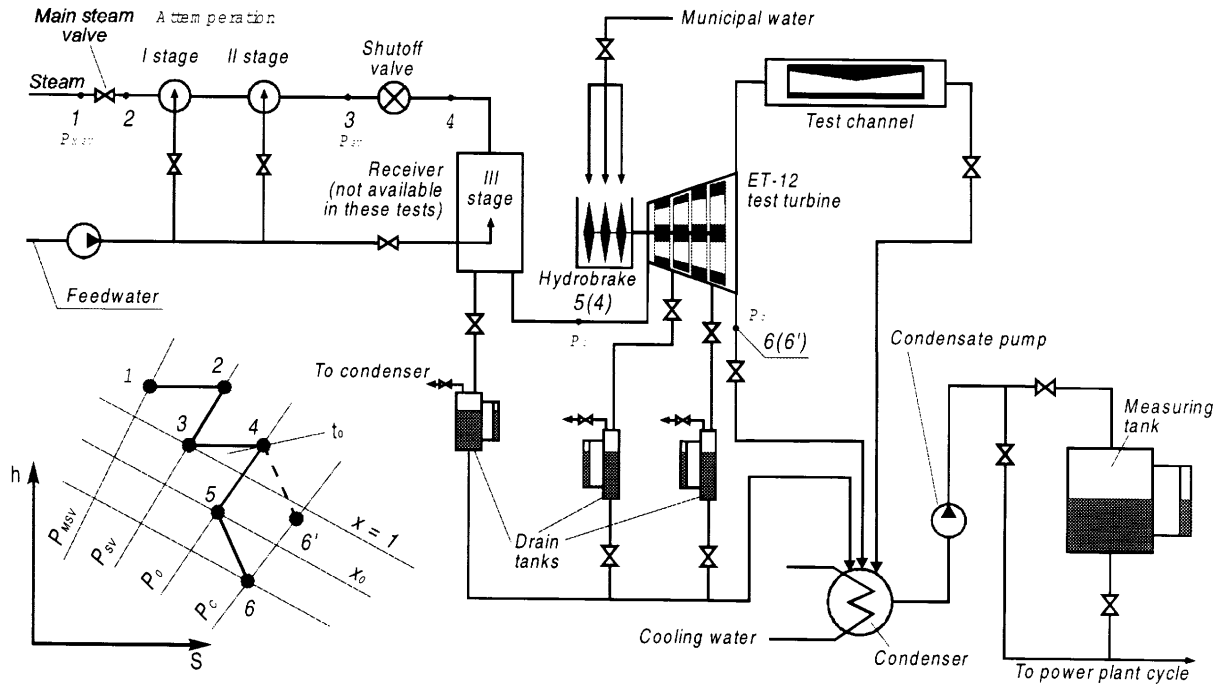


Figure 2-2
Cycle Diagram of the Test Rig

The cycle includes three stages of steam attemperation. The first two stages consist of centrifugal jets installed at a distance of 15 and 20 m from the turbine throttle valve. The attemperation in these stages is performed with condensate or feedwater at saturation temperature. This provides the required steam superheat at the turbine inlet $\Delta T_0 = T_0 - T_s(p_0)$. Control of the inlet pressure p_0 is performed by steam throttling in the throttle valve between points 3 and 4 (Figure 2-2).

The inlet steam dryness $x < 1$ is achieved with the third attemperation system which consists of steam jets installed in the receiver. In this study the third attemperation system was not in use.

The turbine which is installed upstream of the test channel provides the steam parameters required. By varying the steam parameters at point 5 (Figure 2-2) the required steam moisture is produced with corresponding droplet size. In addition, the droplet size is monitored with the laser probe (see Special Systems of Measurement – Moisture and Droplet Size subsection).

The exhaust steam from the turbine and the wet steam rig (Test Channel) is directed into the condenser, and the steam condensate is pumped into the measuring tank to measure the steam flowrate through the turbine. After the measuring tank, the condensate is returned into the power plant cycle.

The system of measurement of the test turbine includes:

- Measurement of rpm with an electronic digital frequency meter. A photodiode acts as the primary rpm sensor. It provides a signal from light impulses generated by a perforated disk. The signal from the sensors is amplified and goes to the frequency meter and the electronic

overspeed governor. The error in the rpm measurement is ± 10 rpm at measurement time 0.6 s or ± 1 rpm at measurement time 6 s.

- Measurement of torque is accomplished with a dial balance gauge with a scale factor of 10 g.
- Measurement of steam and feedwater temperature is performed by platinum resistance thermometers.
- Measurement of static and total stagnation pressures by specially manufactured and calibrated probes and heads. Pressure heads and impulse lines are purged with air just before each measurement. The pressure is measured by preamps and digital integrating voltmeters, and by standard pressure gauges.
- Measurement of steam flowrate is accomplished with the measuring tank, calibrated by taking into account the condensate temperature. Drain flowrate is measured with calibrated drain vessels.

All the systems of measurement (temperature, absolute pressure, pressure drops), excluding steam flowrate, are duplicated to check validity of measurements during each test.

Test Rig for Study of Moisture Precipitation and Impurities Concentration in Early Liquid Films

The special wet steam test rig was developed to study flow and generation of liquid films in two-phase flow in the presence of fine droplets ($r_d \leq 1 \mu\text{m}$). It includes a profiled nozzle installed at the exit of the test turbine. The general view of the wet steam test rig is shown in Figure 2-3.

The working part of the test rig is the flat nozzle with a movable upper profile and a bottom horizontal plate (Figure 2-4). The latter has fluoroplastic thermal insulation.

The metal plate 1 mm thick has six liquid film thickness gauges, seven static pressure taps, six thermosensors (based on Chromel-Copel thermocouples) for measurement of metal temperature, and six thermosensors (based on Chromel-Copel thermocouples) for measurement of flow temperature on the wall (Figure 2-5).

The liquid flowrate in the film is measured by extracting the liquid through the liquid intake slots 1 mm wide to the volumetric vessels. The vessels were thoroughly calibrated taking into account the liquid temperature.

Wet steam inevitably passes through the intake slots together with the liquid film. To prevent steam ingress into the vessel, it is removed with suction and discharged to the condenser (see Figure 2-10 further in this section).

Seven static pressure taps 1 mm in diameter are installed on the bottom plate to study static pressure distribution along the channel.

Total stagnation pressure at the nozzle inlet is measured with the special probe described previously⁽¹⁾. The feature of this probe is that the head section for stagnation measurement has a fairing, which provides measurement independent of the angle of flow ($\pm 35^\circ$). This head design also provides less errors during wet steam measurements.

Figure 2-6 shows views of the working part (the plate), where the parameters of the generated liquid film and accompanying steam flow were measured. The film thickness gauges, the calibration rig, and the principles of operation have been detailed previously⁽¹⁾.

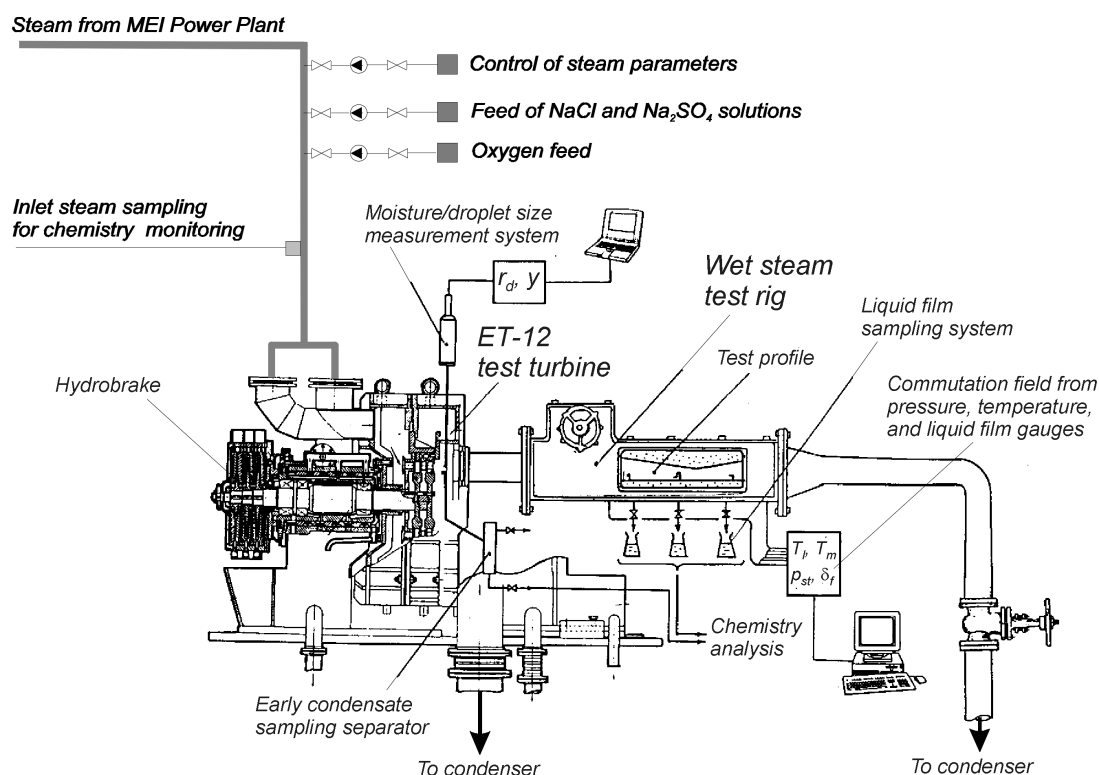


Figure 2-3
General View of the Wet Steam Test Rig Installed at the Exit of the Test Turbine



Figure 2-4
The Wet-Steam Rig with the Test Turbine Installed Upstream (a); the Working Part of the
Rig (b); the Test Channel with the Movable Upper Profile (c)

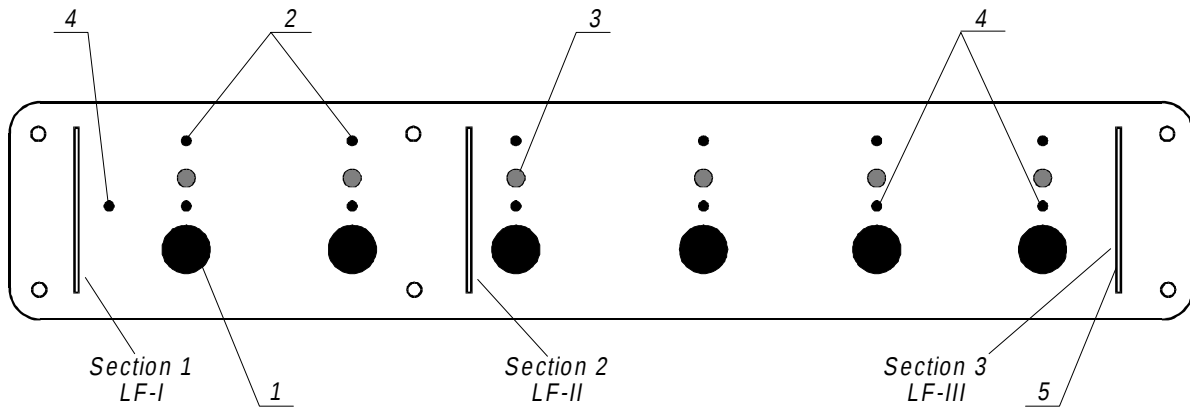


Figure 2-5
Location of Sensors on the Surface of the Working Plate

1 – film thickness gauges; 2 – metal temperature thermocouples; 3 – wall flow temperature thermocouples; 4 – static pressure taps; 5 – liquid intake slots

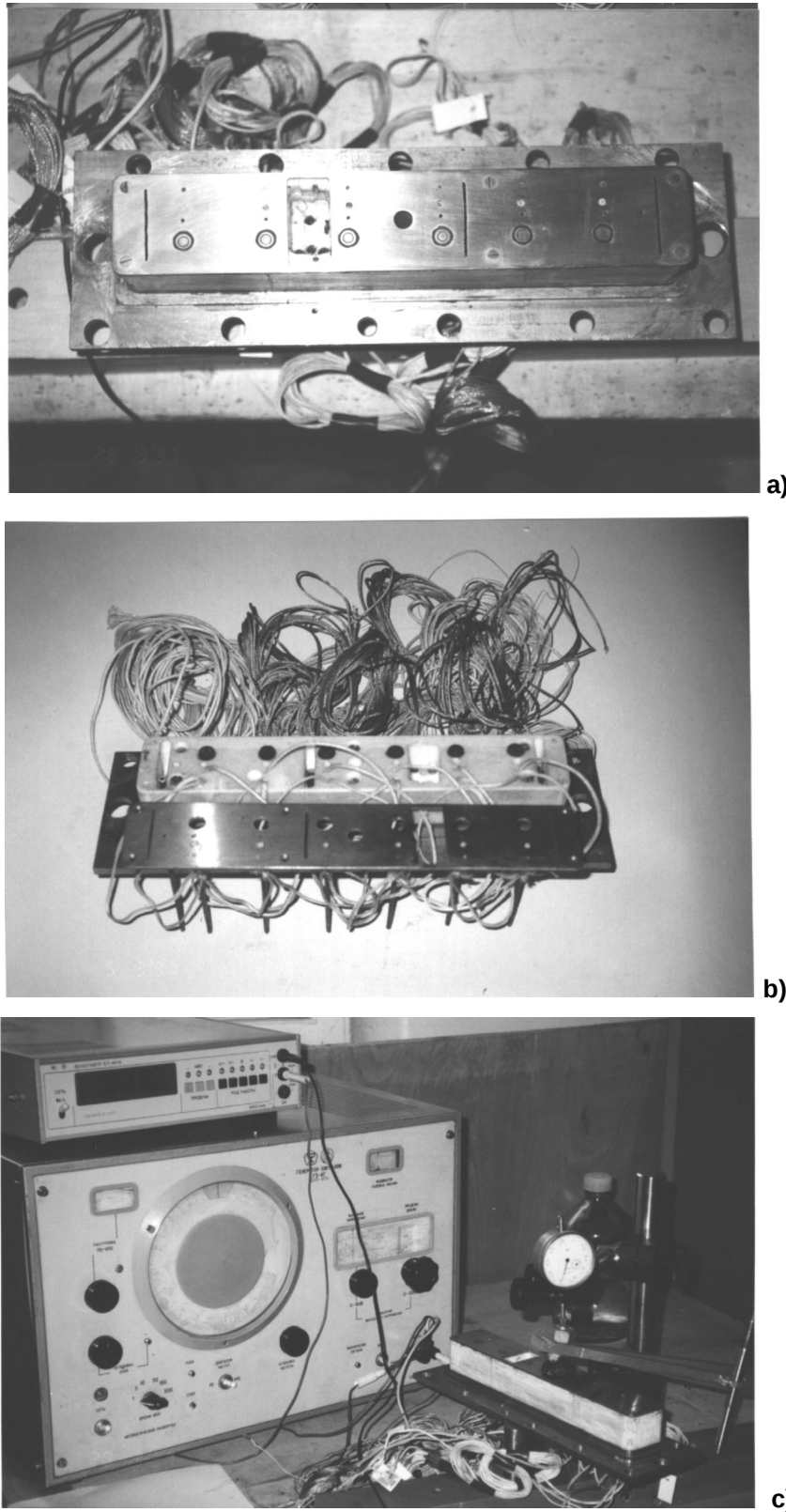


Figure 2-6
Working Plate for Study of Deposition (a, b) and Calibration Rig for the Liquid Film Gauges (c)

Special Systems of Measurement

Moisture and Droplet Size

For these series of moisture/droplet size measurements downstream of the test turbine, a new laser probe was manufactured (Figure 2-7). The probe is installed downstream of the turbine at the inlet to the test channel (Figure 2-7, a). The design of the probe head is the same as for previous work⁽¹⁾. A gaseous laser with 0.6328 μm wavelength is used as the monochromatic light source. The diagram and description of the probe are detailed in reference 1. Figure 2-7 (b) shows a diagram of the droplet size and moisture measurements.

Inlet Steam Sampling System

The inlet steam sampling system, chemistry parameters monitored, analytical procedures and instruments used are detailed in reference 1. A view of on-line analyzers of the inlet steam sampling system is shown in Figure 2-8.

Early Condensate Sampling System

The early condensate sampling system consists of an early condensate probe (similar to that used in reference 1) installed downstream of the rotating Curtis blading and upstream of the inlet section of the wet steam test rig and auxiliary devices. The latter include: a separator for separation of steam and the early condensate and a vessel for periodical sampling of the early condensate for analysis (Figures 2-3 and 2-9).

The probe head is installed in the middle section along the blade length and is directed against the steam flow from the rotating blading.

The early condensate probe, the separator, and the tubing are manufactured from stainless steel. All the system components external to the turbine have thermal insulation to provide adiabatic sampling.

The error of the early condensate sampling was 3%.

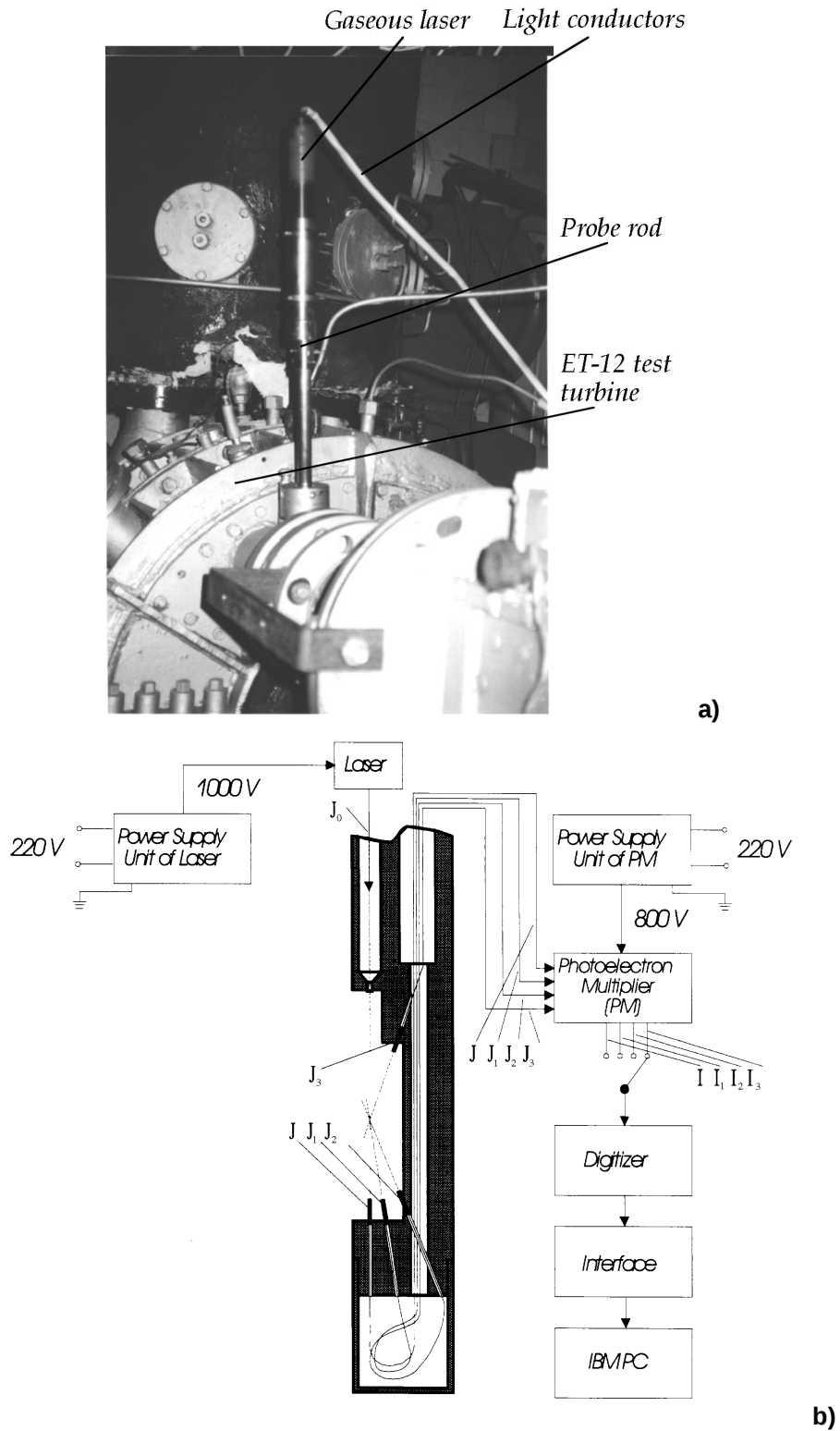


Figure 2-7
Laser Probe Installed at the ET-12 Test Turbine (a); Probe Measurement Diagram (b)



Figure 2-8
A View of On-Line Analyzers of the Inlet Steam Sampling System

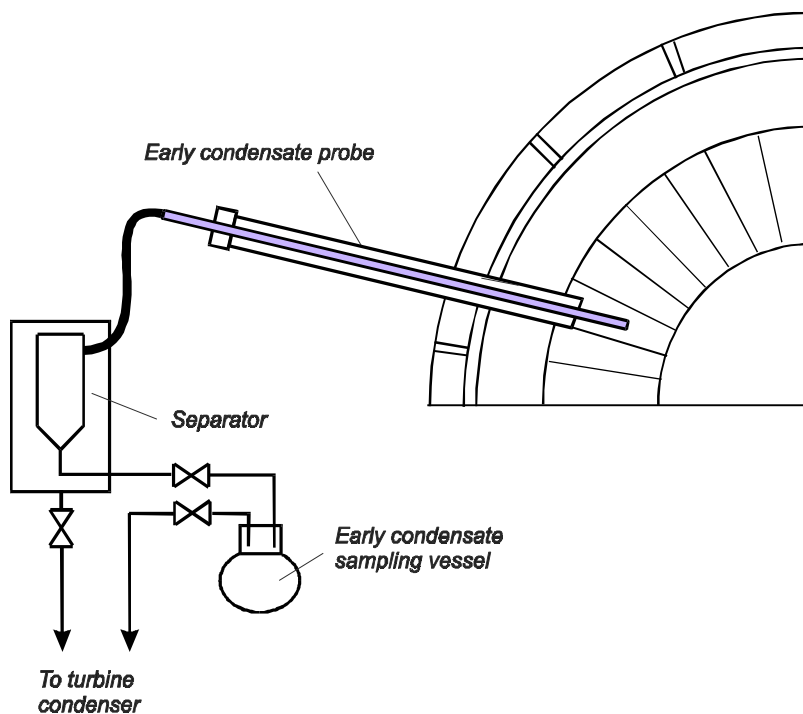


Figure 2-9
Early Condensate Sampling System

Liquid Film Sampling System

Sampling of the liquid film generated on the plate surface for chemistry monitoring is performed by extraction of the liquid to the vessels for periodical sampling of the liquid films through the liquid intake slots 1 mm wide. The first slot along the steam flow (Figure 2-5) is for removal of any liquid film generated on the surface upstream of the studied section.

To prevent distortion of the wet-steam flow parameters, the liquid film sampling is performed immediately after measurement of all monitored parameters of the steam flow.

The liquid film sampling method through the intake slots was selected experimentally. The operation of two specially developed sampling systems – gravitational and forced – was checked.

The first (gravitational) method (Figure 2-10, a) is preferential. The film is accumulated in the sampling vessel by passing through the liquid intake slots under action of gravitational forces. The second (forced) method (Figure 2-10, b) requires some minimum pressure drop in the intake slot. This method has some disadvantages, because in spite of discharge to the condenser of the steam extracted with the liquid film, part of the steam remains in the sample diluting it.

However, preliminary tests indicated, that the gravitational method did not work meanfully under the conditions of this study. Visual observation revealed that in the slot area a local stagnation of liquid film occurred. The film then bent around this area. Thus the forced sampling method of the liquid film was implemented in this study.

Taking into account that the liquid film sample is diluted with condensed steam, the amount of steam which entered the vessel through the intake slots was measured experimentally. These data were used for correction of results.

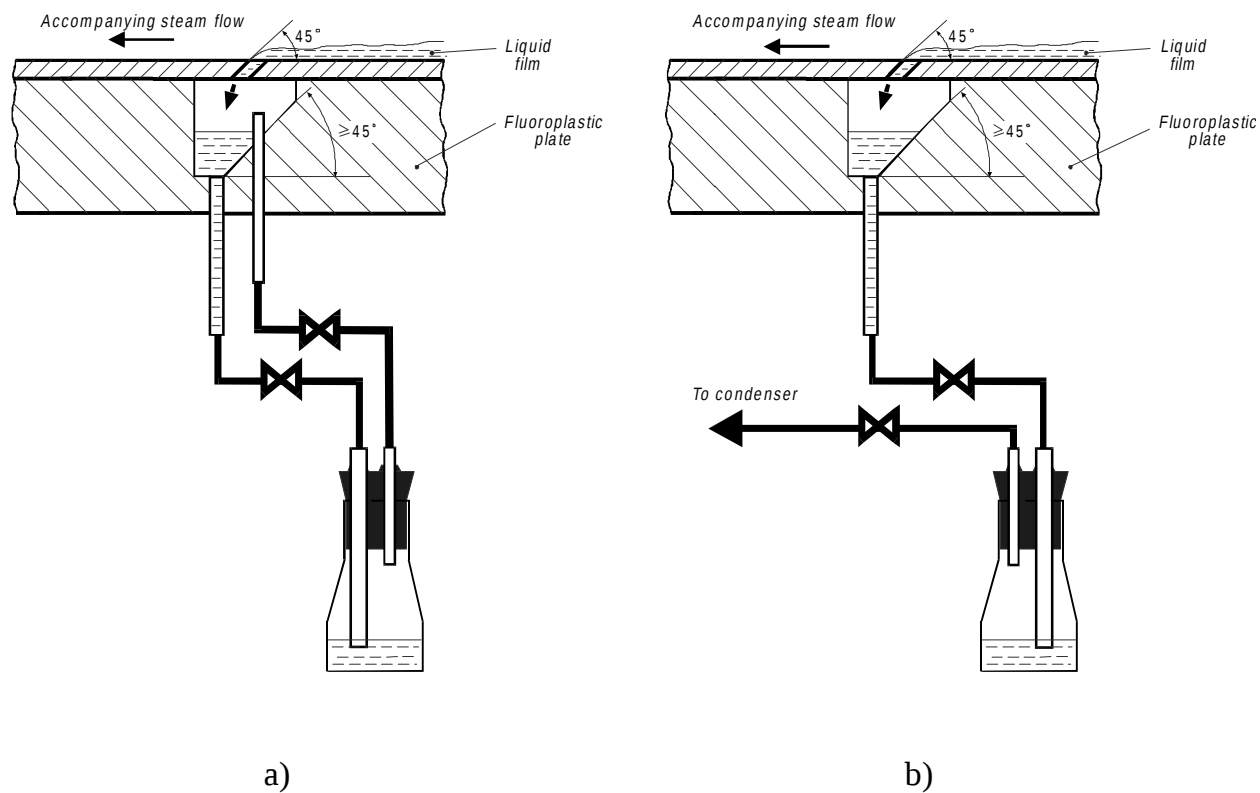


Figure 2-10
Gravitational (a) and Forced (b) Liquid Film Sampling Systems

References

1. *Turbine Steam Chemistry and Corrosion. Experimental Turbine Tests.* Electric Power Research Institute, Palo Alto, CA: September 1997. Report TR-108185.

3

DISCUSSION OF RESULTS

Effect of Steam Chemistry and Impurity Level in Turbine Inlet Steam on the Content of Impurities in the Early Condensate and the Liquid Film

Steam extracted from the MEI Power Plant was used in the tests to study the influence of different chemistries on the composition of the early condensate and liquid films, as well as on the droplet size, moisture levels, and film thickness. At normal operating conditions the feedwater chemistry of the MEI Power Plant is controlled with ammonia ($\text{pH} = 9.0 \pm 0.2$) and the boiler chemistry with Na_3PO_4 (3 – 4 ppm).

The tests were performed with the following chemistries:

- PT3.0 – means addition of ammonia to the feedwater and phosphate ($\text{Na}:\text{PO}_4 = 3.0$) to the boiler. No additions to the inlet steam of the test turbine.
- PT3.0 + NaCl – means addition of ammonia to the feedwater and phosphate ($\text{Na}:\text{PO}_4 = 3.0$) to the boiler, with addition of NaCl solution to the inlet steam of the test turbine.
- PT3.0 + Na_2SO_4 – means addition of ammonia to the feedwater and phosphate ($\text{Na}:\text{PO}_4 = 3.0$) to the boiler, with addition of Na_2SO_4 solution to the inlet steam of the test turbine.
- OT – means addition of a reduced level of ammonia to the feedwater ($\text{pH} = 8.5 - 8.7$) and no phosphate added to the boiler, with addition of oxygen to the inlet steam of the test turbine.
- OT + NaCl – means addition of a reduced level of ammonia to the feedwater ($\text{pH} = 8.5 - 8.7$) and no phosphate added to the boiler, with addition of NaCl solution and oxygen added to the inlet steam of the test turbine.
- OT + Na_2SO_4 – means addition of a reduced level of ammonia to the feedwater ($\text{pH} = 8.5 - 8.7$) and no phosphate added to the boiler, with addition of Na_2SO_4 solution and oxygen added to the inlet steam of the test turbine.

The basic chemistry and operating parameters during the tests are listed in Table A-1 (see Appendix). The results of chloride, sulfate, and pH measurements in the early condensate and the liquid film at each chemistry studied are given in Tables 3-1 – 3-4.

Table 3-1

Chloride Results with PT3.0 (EC is early condensate; LF-II and LF-III are liquid films extracted at Sections 2 and 3 respectively (see Figure 2-5); n is concentration ratio)

Parameter	Inlet Steam	EC		LF – II		LF – III	
		Content	n	Content	n	Content	n
Cl, ppb	2.0	55.8	27.9	385.9	193.0	604.3	302.2
pH	9.3	6.8		6.3		6.3	
Cl, ppb	6.7	118.2	31.4	1300	194.0	1845	275.4
pH	9.2	6.3		6.4		6.3	
Cl, ppb	15.5	191.0	12.3	2296	148.1	3175	204.8
pH	9.2	6.8		6.3		6.6	
Cl, ppb	35.4	295.3	8.3	6485	168.9	5274	137.3
pH	9.2	6.5		6.5		6.7	

Table 3-2

Chloride Results with OT (EC is early condensate; LF-II and LF-III are liquid films extracted at Sections 2 and 3 respectively (see Figure 2-5); n is concentration ratio)

Parameter	Inlet Steam	EC		LF – II		LF – III	
		Content	n	Content	n	Content	n
Cl, ppb	7.5	38.0	5.1	620.1	82.7	982.0	130.9
DO, ppb	290						
pH	8.5	6.3		6.6		6.3	
Cl, ppb	24.0	160.4	6.7	1737	72.4	1333	55.5
DO, ppb	250						
pH	8.6	5.9				5.9	
Cl, ppb	29.1	178.3	6.1	1805	62.0	992	34.1
DO, ppb	230						
pH	8.6	5.9				5.9	
Cl, ppb	41.3	98.5	2.4	709.4	17.2	1928	46.7
DO, ppb	180						
pH	8.5	6.3		6.3		6.3	

Table 3-3

Sulfate Results with PT3.0 (EC is early condensate; LF-II and LF-III are liquid films extracted at Sections 2 and 3 respectively (see Figure 2-5); n is concentration ratio)

Parameter	Inlet Steam	EC		LF – II		LF – III	
		Content	n	Content	n	Content	n
SO ₄ ppb	2.0	67.6	33.8	319.4	159.7	742.7	371.4
pH	9.3	6.7		6.7		6.7	
SO ₄ ppb	19.9	147.9	7.4	490.0	24.6	1402	70.4
pH	9.3	6.5		6.5		6.7	
SO ₄ ppb	23.1	102.3	4.4	652.3	28.2	2133	92.3
pH	9.3	6.9		6.5		6.4	
SO ₄ ppb	35.5	142.3	4.0	520.4	14.7	5274	148.6
pH	9.2	6.9		6.5		6.5	
SO ₄ ppb	38.4	229.1	6.1	930.0	24.2	3802	99.0
pH	9.4	6.5		6.5		6.7	
SO ₄ ppb	66.9	275.4	4.1	2802	41.9	4082	61
pH	9.3	6.9		6.5		6.4	

Table 3-4

Sulfate Results with OT (EC is early condensate; LF-II and LF-III are liquid films extracted at Sections 2 and 3 respectively (see Figure 2-5); n is concentration ratio)

Parameter	Inlet Steam	EC		LF – II		LF – III	
		Content	n	Content	n	Content	n
SO ₄ , ppb	7.0	42.8	6.1	247.8	35.4	1223	174.7
DO, ppb	210						
pH	8.7	6.3		6.3		6.3	
SO ₄ , ppb	15.2	95.9	6.3	544.4	35.8	1513.5	99.6
DO, ppb	260						
pH	8.6	6.5		6.3		5.7	
SO ₄ , ppb	55.4	158.5	2.9	1102	19.9	2587	46.7
DO, ppb	320						
pH	8.6	6.6		6.3		6.3	

Early Condensate Chemistry Data

The composition of steam supplied during the PT3.0 tests was as follows: pH = 9.1 – 9.4; Na = 1.0 – 1.8 ppb; Cl = 2.0 – 3.7 ppb; SO₄ = 2.0 – 3.2 ppb; DO ≤ 5 ppb, and during the OT tests it was as follows: pH = 8.4 – 8.6; Na = 0.7 – 1.2 ppb; Cl = 2.0 – 2.4 ppb; SO₄ = 2.0 – 2.7 ppb. The distinctive feature of the OT tests was that the feed of ammonia in the feedwater was decreased, and the feed of phosphate into boiler water was turned off 24 hours approximately before each OT test. During these tests oxygen was introduced into the inlet steam of the test turbine (180 – 350 ppb).

The PT3.0 and OT tests were performed at several chloride and sulfate levels in the turbine inlet steam. Changes in the level of these impurities at the inlet were accomplished by feeding NaCl and Na₂SO₄ solutions into the inlet steam.

The experimental data indicate, that the basic trends of the behavior of these impurities in the early condensate produced during the current and the previous phases of the project⁽¹⁾ are the same. Thus, the content of chloride and sulfate in the early condensate depends on the level in the inlet steam: it increases non-linearly with increase in chloride/sulfate concentration in the inlet steam (Tables 3-1 – 3-4, Figures 3-1 and 3-2). These experimental data may be approximated by the following equations:

$$C_{\text{Cl-EC}}^{\text{PT3.0}} = 381 \times (C_{\text{Cl-IS}}^{\text{PT3.0}})^{0.58} \quad (\text{eq. 3-1})$$

$$C_{\text{SO}_4\text{-EC}}^{\text{PT3.0}} = 47.2 \times (C_{\text{SO}_4\text{-IS}}^{\text{PT3.0}})^{0.37} \quad (\text{eq. 3-2})$$

$$C_{\text{Cl-EC}}^{\text{OT}} = 10 \times (C_{\text{Cl-IS}}^{\text{OT}})^{0.75} \quad (\text{eq. 3-3})$$

$$C_{\text{SO}_4\text{-EC}}^{\text{OT}} = 14.9 \times (C_{\text{SO}_4\text{-IS}}^{\text{OT}})^{0.61} \quad (\text{eq. 3-4})$$

where $C_{\text{Cl-EC}}^{\text{PT3.0}}$, $C_{\text{SO}_4\text{-EC}}^{\text{PT3.0}}$, $C_{\text{Cl-EC}}^{\text{OT}}$, and $C_{\text{SO}_4\text{-EC}}^{\text{OT}}$ are the levels of chloride and sulfate in the early condensate with PT3.0 and OT; $C_{\text{Cl-IS}}^{\text{PT3.0}}$, $C_{\text{Cl-IS}}^{\text{OT}}$, $C_{\text{SO}_4\text{-IS}}^{\text{PT3.0}}$, $C_{\text{SO}_4\text{-IS}}^{\text{OT}}$ are the levels of chloride and sulfate in the inlet steam with PT3.0 and OT. Hereinafter the levels of chloride and sulfate calculated with the power fit equations (3-1 – 3-4) will be used in the analysis; the low level of impurities in the inlet steam is taken as 2 ppb, and the high level as 40 ppb.

It was found that higher levels of chloride and sulfate were measured in the early condensate when using PT3.0 (*ca.* 2 – 3.4 -fold and *ca.* 1.3 – 2.7 -fold respectively) as compared with those for OT. For example, at low concentration of the test impurities in the inlet steam (2 ppb), the level of chloride and sulfate in the early condensate calculated with the power fit equations (3-1 – 3-4) with PT3.0 is 56.9 and 61 ppb respectively, and with OT is 16.8 and 22.7 ppb respectively. But the difference in chloride and sulfate levels in the EC with PT3.0 and OT in the current tests is less compared with the previous data⁽¹⁾ (Figure 3-1 and 3-2). The trend for the chloride and sulfate levels in the EC with PT3.0 (current tests) basically follows the points of the previous data⁽¹⁾, whereas the OT levels are slightly higher. The results also show, that at minimum concentration of impurities in the inlet steam the levels of chloride and sulfate in the EC are almost the same, whereas the level of chloride in the EC becomes slightly higher than the level of sulfate with increase in the inlet steam concentrations.

From the test data on the content of chloride and sulfate in the inlet steam and the early condensate, the concentration ratios «n» for chloride and sulfate for the different chemistries were calculated (Figures 3-3 and 3-4):

$$n_{\text{Cl-EC}} = \frac{C_{\text{Cl-EC}}}{C_{\text{Cl-IS}}} \quad (\text{eq. 3-5})$$

$$n_{\text{SO}_4\text{-EC}} = \frac{C_{\text{SO}_4\text{-EC}}}{C_{\text{SO}_4\text{-IS}}} \quad (\text{eq. 3-6})$$

where $n_{\text{Cl-EC}}$ and $n_{\text{SO}_4\text{-EC}}$ are the concentration ratios of chloride and sulfate; $C_{\text{Cl-EC}}$ and $C_{\text{SO}_4\text{-EC}}$ are the content of chloride and sulfate in the early condensate respectively; $C_{\text{Cl-IS}}$ and $C_{\text{SO}_4\text{-IS}}$ are the content of chloride and sulfate in the inlet steam respectively.

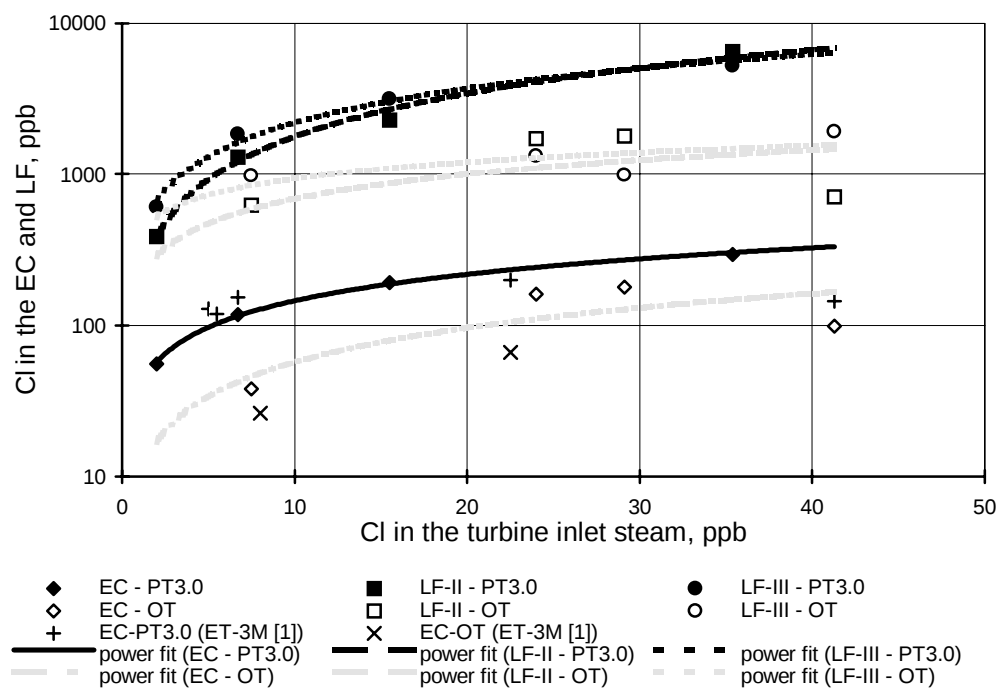


Figure 3-1
Content of Chloride in the Early Condensate and the Liquid Films Vs. Level of Chloride in the Turbine Inlet Steam

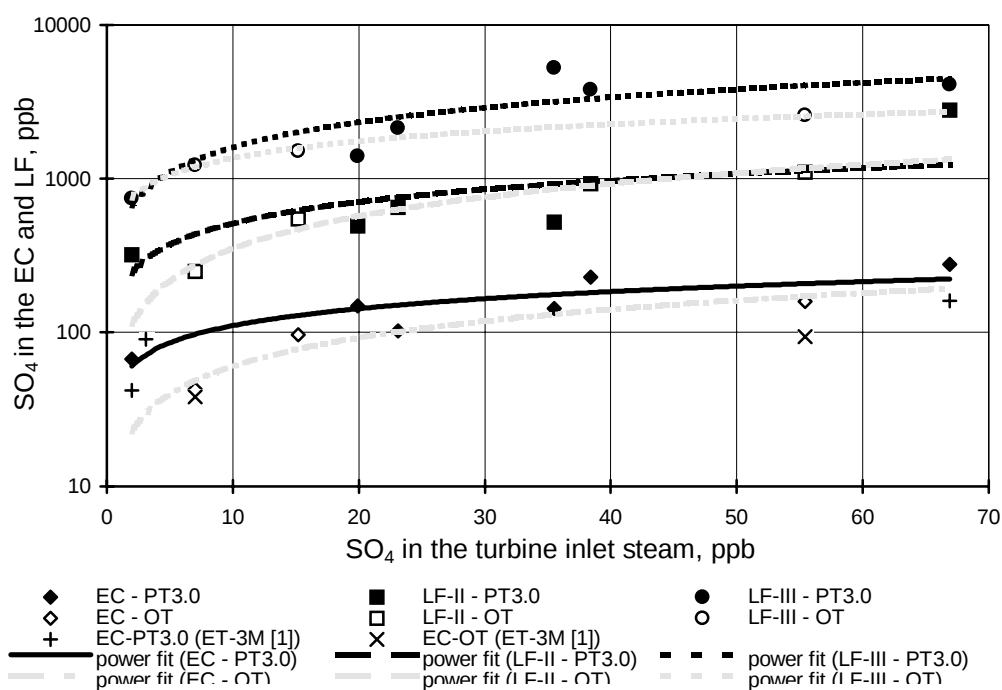


Figure 3-2
Content of Sulfate in the Early Condensate and the Liquid Films Vs. Level of Sulfate in the Turbine Inlet Steam

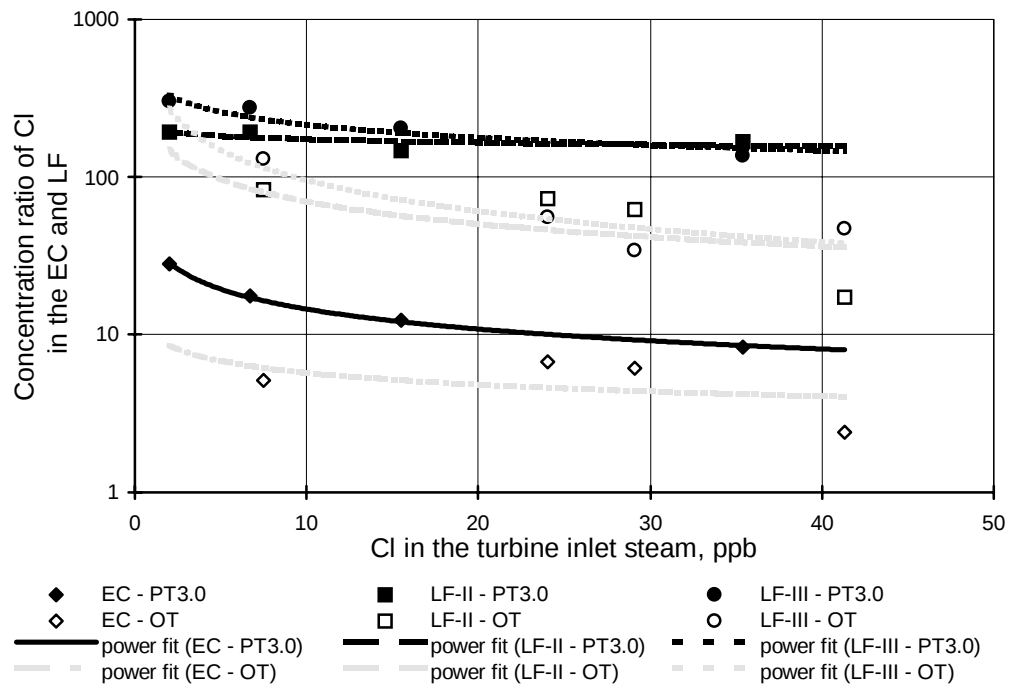


Figure 3-3
Concentration Ratio of Chloride in the Early Condensate and the Liquid Films Vs. Level of Chloride in the Turbine Inlet Steam

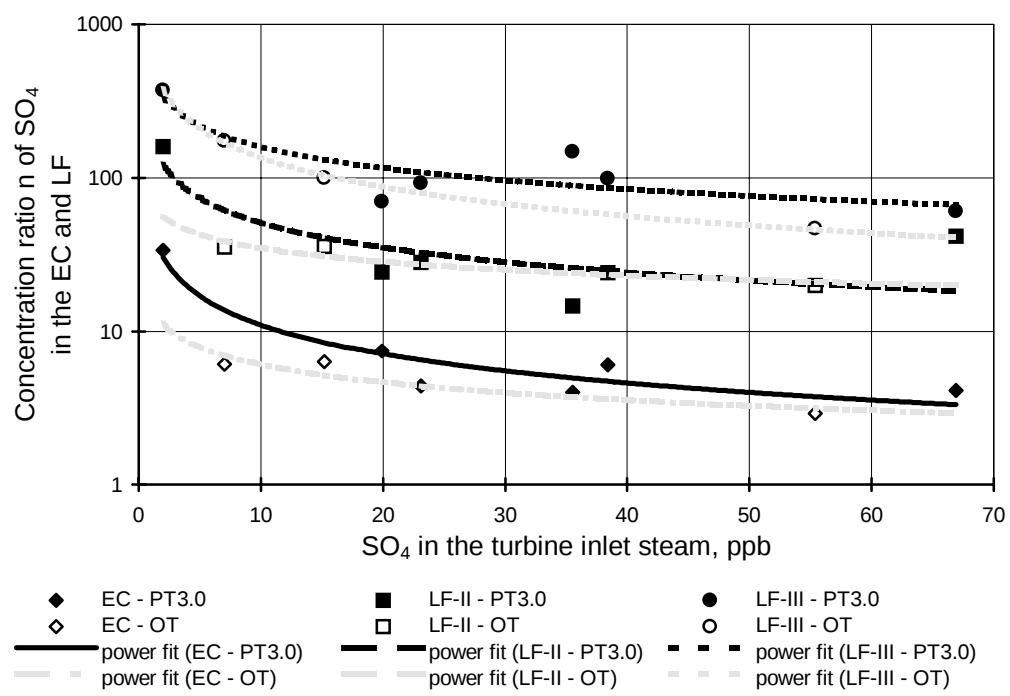


Figure 3-4
Concentration Ratio of Sulfate in the Early Condensate and the Liquid Films Vs. Level of Sulfate in the Turbine Inlet Steam

The data on the concentration ratios (Tables 3-1 – 3-4, Figures 3-3 and 3-4) show that the highest concentration ratio of chloride and sulfate is with PT3.0, and the lowest is with OT. The concentration ratio of both chloride and sulfate decreases with increase in the level of these impurities in the inlet steam. All this is in agreement with the previous tests⁽¹⁾.

Comparison of the concentration ratios of chloride and sulfate in the early condensate for the same chemistry shows that at minimum level of impurities the concentration ratios of both species are almost the same, and with increasing inlet levels chloride concentrates slightly higher in the EC than sulfate.

During all tests the pH of the EC was significantly lower than the pH of the inlet steam: for the PT3.0 chemistry these values were 6.3 – 6.9 compared with 9.2 – 9.4 (IS); and for the OT chemistry they were 5.9 – 6.6 compared with 8.5 – 8.7 (IS).

The level of phosphate in IS and EC with PT3.0, and the level of oxygen in EC with OT were below the sensitivity of measurement (<10 ppb for phosphate and <5 ppb for oxygen).

Liquid Film Chemistry Data

The sampling and chemistry analysis of liquid films in sections No. 2 (LF-II) and No. 3 (LF-III) along the nozzle length (see Section 2, Figure 2-5) was performed simultaneously with the EC sampling/analysis. The corresponding test results are shown in Tables 3-1 – 3-4 and Figures 3-1 and 3-2. The pattern of impurity behavior in the LF is practically the same as in the EC. Again, for comparison, the test data are approximated by the following equations:

$$C_{\text{Cl-LFII}}^{\text{PT3.0}} = 197.8 \times (C_{\text{Cl-IS}}^{\text{PT3.0}})^{0.95} \quad (\text{eq. 3-7})$$

$$C_{\text{SO}_4\text{-LFII}}^{\text{PT3.0}} = 1761 \times (C_{\text{SO}_4\text{-IS}}^{\text{PT3.0}})^{0.46} \quad (\text{eq. 3-8})$$

$$C_{\text{Cl-LFII}}^{\text{OT}} = 1961 \times (C_{\text{Cl-IS}}^{\text{OT}})^{0.54} \quad (\text{eq. 3-9})$$

$$C_{\text{SO}_4\text{-LFII}}^{\text{OT}} = 69.2 \times (C_{\text{SO}_4\text{-IS}}^{\text{OT}})^{0.7} \quad (\text{eq. 3-10})$$

$$C_{\text{Cl-LFIII}}^{\text{PT3.0}} = 389.5 \times (C_{\text{Cl-IS}}^{\text{PT3.0}})^{0.75} \quad (\text{eq. 3-11})$$

$$C_{\text{SO}_4\text{-LFIII}}^{\text{PT3.0}} = 457.2 \times (C_{\text{SO}_4\text{-IS}}^{\text{PT3.0}})^{0.54} \quad (\text{eq. 3-12})$$

$$C_{\text{Cl-LFIII}}^{\text{OT}} = 402.2 \times (C_{\text{Cl-IS}}^{\text{OT}})^{0.37} \quad (\text{eq. 3-13})$$

$$C_{\text{SO}_4\text{-LFIII}}^{\text{OT}} = 5819 \times (C_{\text{SO}_4\text{-IS}}^{\text{OT}})^{0.37} \quad (\text{eq. 3-14})$$

One of the most important conclusions is that the concentration of impurities in the liquid films is much higher than in the early condensate. For example, at low concentration of chloride and sulfate in the inlet steam, the concentration in the liquid film (averaged by two sampling

sections) with PT3.0 is about 9.1 (Cl) and about 7.4 (SO₄) times higher, than in the EC. For OT these figures are about 23.9 (Cl) and about 19 (SO₄) higher than in the equivalent EC.

Therefore, the tests performed indicate that the ratio of concentration of impurities in the LF as relative to the EC with OT is higher than with PT3.0. The possible mechanism of this phenomenon is explained later in this section (see subsection “Effect of Steam Chemistry and Impurity Level on the Distribution of Temperatures and the Formation of Liquid Films”). Nevertheless, the absolute values of the impurities with OT are always lower than with PT3.0.

The analysis of the data produced also indicates the following:

- *Effect of inlet steam concentration.* As in the EC case, the concentrations of chloride and sulfate in the LF depend on the content of these impurities in the inlet steam: they increase non-linearly with concentration in the inlet steam.
- *Effect of chemistry.* The concentration of both chloride and sulfate in the LF with PT3.0 is higher than with OT. In the case of chloride, the level in the LF-II and LF-III with PT3.0 is about 1.3 – 4.6 and about 1.3 – 3.9 times higher respectively than with OT. A similar pattern for sulfate is less evident. In general, both the PT3.0 and OT test results for sulfate seem to be close to each other for the same condition. Nevertheless, there is a small trend to increased concentration of sulfate in the liquid films (averaged by two sampling sections) with PT3.0 compared with OT over the studied impurity range in the inlet steam up to about 1.4 times.
- *Effect of sampling location along the nozzle.* The concentration of impurities in the liquid films taken from the Section No. 3 is higher than that from the Section No. 2. For example, at low concentration of chloride and sulfate in the inlet steam, the level in the LF-III with PT3.0 is about 1.7 (Cl) and about 1.9 (SO₄) times higher, than in the LF-II. For OT these figures are: about 1.8 (Cl) and about 6.7 (SO₄). The possible reason for this is explained later in this section (see subsection “Effect of Steam Chemistry and Impurity Level on the Distribution of Temperatures and the Formation of Liquid Films”).

In most cases the concentration of chloride in the LF is much higher than that of sulfate at the same concentration of impurities in the inlet steam.

From the test data on the concentration of chloride and sulfate in the inlet steam and the liquid films, the concentration ratios «n» for chloride and sulfate for different chemistries were calculated:

$$n_{\text{Cl-LF}} = \frac{C_{\text{Cl-LF}}}{C_{\text{Cl-IS}}} \quad (\text{eq. 3-15})$$

$$n_{\text{SO}_4\text{-LF}} = \frac{C_{\text{SO}_4\text{-LF}}}{C_{\text{SO}_4\text{-IS}}} \quad (\text{eq. 3-16})$$

where $n_{\text{Cl-LF}}$ and $n_{\text{SO}_4\text{-LF}}$ are the concentration ratios of chloride and sulfate; $C_{\text{Cl-LF}}$ and $C_{\text{SO}_4\text{-LF}}$ are the content of chloride and sulfate in the liquid film respectively; $C_{\text{Cl-IS}}$ and $C_{\text{SO}_4\text{-IS}}$ are the content of chloride and sulfate in the inlet steam respectively.

These data (Figures 3-3 and 3-4) show that, as in the EC case, the highest concentration ratio of chloride and sulfate in the liquid films is with PT3.0, and the lowest is with OT. The concentration ratio of both chloride and sulfate decreases with increase in the concentration of these impurities in the inlet steam. Again, the concentration ratios of chloride are higher than that of sulfate for the same inlet conditions.

During all tests the pH of the LF was significantly lower than the pH of the inlet steam: for the PT3.0 chemistry these values were 6.1 – 6.9 compared with 9.2 – 9.4 (IS); and for the OT chemistry they were 5.7 – 6.6 compared with 8.5 – 8.7 (IS).

A special test was performed to determine the oxygen concentration in the liquid film. During one OT test run, a continuous sample of liquid film was taken from all three sections to collect sufficient sample needed for oxygen determination with the analytical procedure⁽²⁾. It was found that the oxygen concentration in the liquid film, as in the EC, was below the sensitivity of measurement (<5 ppb).

Effect of Inlet Sulfate on Level of Chloride in Early Condensate and Liquid Films

In the previous phase of the project⁽¹⁾, an increase in the sulfate level of the inlet steam resulted in an increase in the chloride level in the early condensate. The same trend was noted in the current tests (Figure 3-5). Moreover, the increase of chloride in the LF was greater than that for the EC.

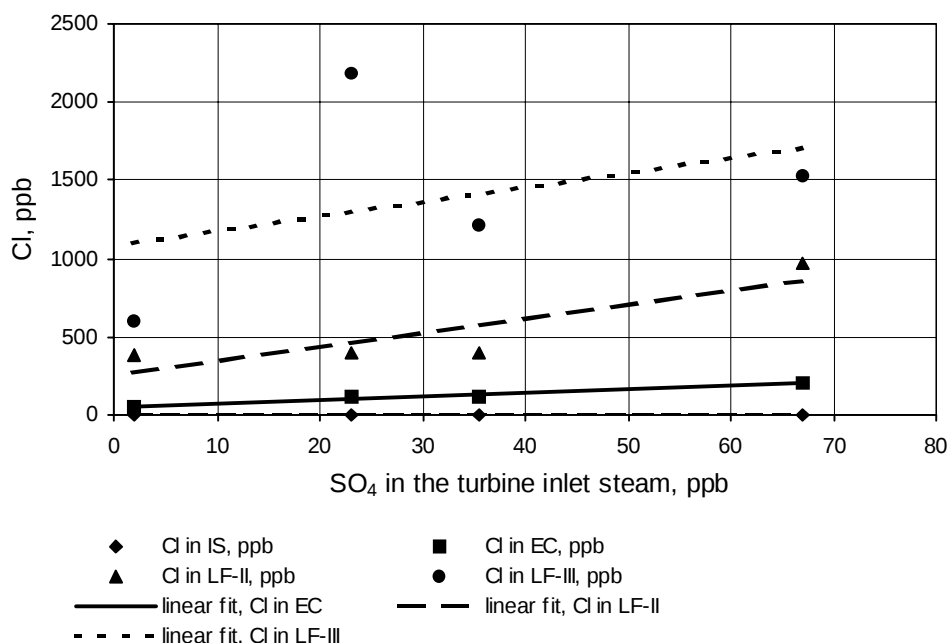


Figure 3-5
Content of Chloride in the Early Condensate and the Liquid Films Vs. Sulfate Level in the Turbine Inlet Steam (CCI in the Inlet Steam is constant (2 ppb))

In summary, the results obtained during this study show that

- Concentration of corrosive impurities in the liquid films formed on the surface of blades and disks can be an order of magnitude higher than that in the EC.
- For the studied chemistries, increase in the level of chloride and sulfate in the inlet steam resulted in increase in the concentration of these impurities in the early condensate and the liquid films.
- Use of PT3.0 chemistry produces the highest concentration (and concentration ratio) of corrosive impurities, and use of OT results in the lowest level (and concentration ratio) of chloride and sulfate in the early condensate and the liquid films.
- The elevated sulfate in the turbine inlet steam results in increased contamination of the early condensate and the liquid films with chloride.
- The pH of the early condensate and the liquid films is about 2-3 pH units lower than the pH of the turbine inlet steam.
- Oxygen does not concentrate in the early condensate and the liquid films.

Effect of Steam Chemistry and Impurity Level on the Moisture and Droplet Size of the Early Condensate

One of the tasks of this series of tests was to study the effects of different chemistries and steam purity on the droplet size of the early condensate generated during steam expansion in the

turbine, and on the measurement of steam moisture downstream of the turbine (at the nozzle inlet).

A special optical probe (see Section 2) was manufactured for the measurement of droplet size (r_d) and moisture (y). The results of r_d and moisture y measurements are given below.

The tests were performed with two chemistries: PT3.0 and OT, and with different concentrations of chloride and sulfate at the turbine inlet. The steam parameters for all the studied chemistries were kept constant; the steam moisture downstream of the turbine was about 0.75%.

Figures 3-6 and 3-7 show droplet size vs. the concentration of chloride and sulfate with PT3.0.

The analysis of these plots shows that microaddition of impurities exerts almost no influence on the droplet size, which is approximately 0.13 μm . Insignificant deviations were within the accuracy of measurement of the probe.

Figures 3-8 and 3-9 show the droplet size vs. the concentration of chloride and sulfate with OT. Here also no effect of impurities on droplet size ($r_d \sim 0.13 \mu\text{m}$) was found.

Therefore, the results obtained show, that replacement of PT3.0 with OT has no influence on the size of droplets generated during steam expansion in the turbine. Also, addition of chloride and sulfate of up to the 70 ppb level doesn't exert any significant influence on the early condensate size. Similar data were produced during the previous tests⁽¹⁾.

The data shown in Figures 3-6 – 3-9 were produced at constant diagram moisture of steam $y_{\text{diagr}} = 0.75\%$, i.e. the steam moisture determined from the Mollier Diagram at the final point of steam expansion in the turbine with account for efficiency. The moisture measured with the optical probe (y_{meas}) was equal to diagram moisture y_{diagr} (i.e. $y_{\text{meas}} = y_{\text{diagr}} = 0.75\%$). But during transition through the saturation line, some difference between the measured moisture and the diagram moisture was found. The moisture was not detected with the optical probe up to $y_{\text{diagr}} \sim 0.2\%$ (Figure 3-10). In the range of $y_{\text{diagr}} = 0.2 - 0.4\%$, y_{meas} was lower than y_{diagr} . In other words, some steam supercooling was determined at $y_{\text{diagr}} \leq 0.4\%$. At $y_{\text{diagr}} > 0.4\%$, the measured moisture and the diagram moisture were the same, i.e. there was equilibrium steam expansion. Similar results were produced during previous tests at the LMZ K-300-240 model turbine⁽³⁾.

Results of droplet size vs. steam moisture at the point of measurement are shown in Figure 3-11. The measurements were performed over a moisture range of 0 – 4%. It is evident that an increase in steam moisture results in droplet size growth.

The moisture and droplet size tests show that at all turbine operating conditions, including chemistry variations (addition of chloride, sulfate, and oxygen), the droplet size of the wet steam flow is in the range of 0.12 – 0.155 μm .

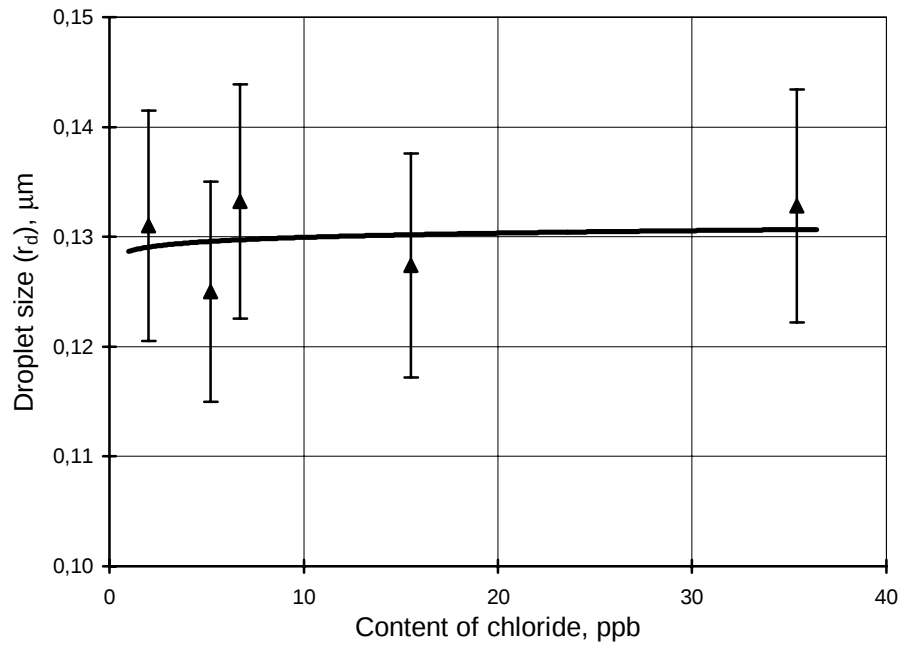


Figure 3-6
Droplet Size Vs. Content of Chloride in the Inlet Steam with PT3.0 ($y = 0.75\%$)

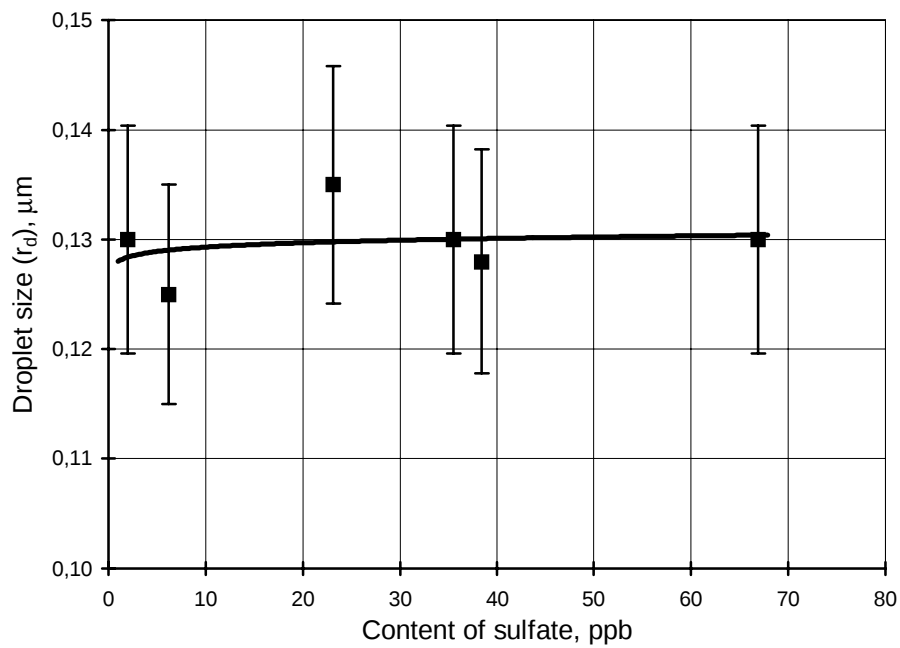


Figure 3-7
Droplet Size Vs. Content of Sulfate in the Inlet Steam with PT3.0 ($y = 0.75\%$)

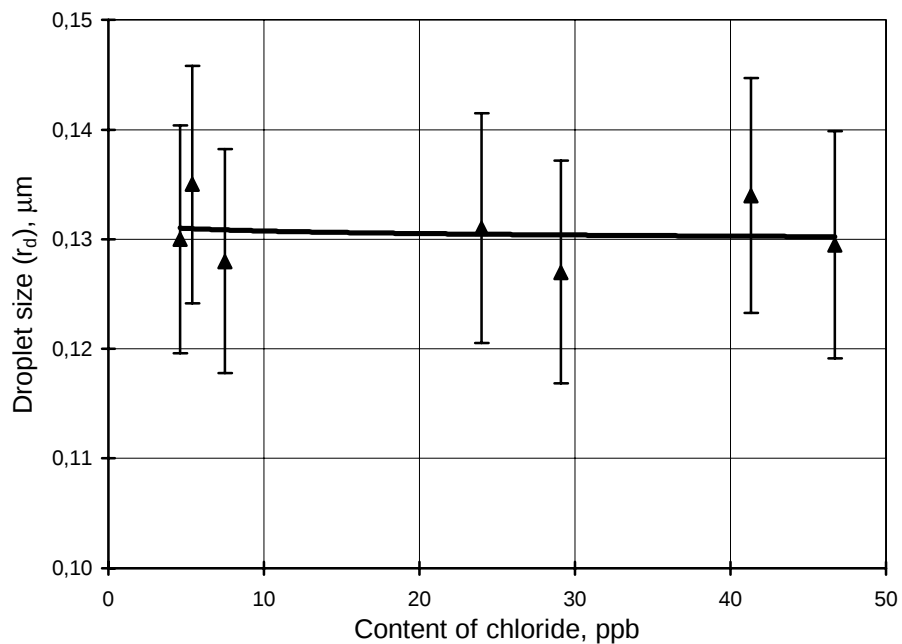


Figure 3-8
Droplet Size Vs. Content of Chloride in the Inlet Steam with OT ($y = 0.75\%$)

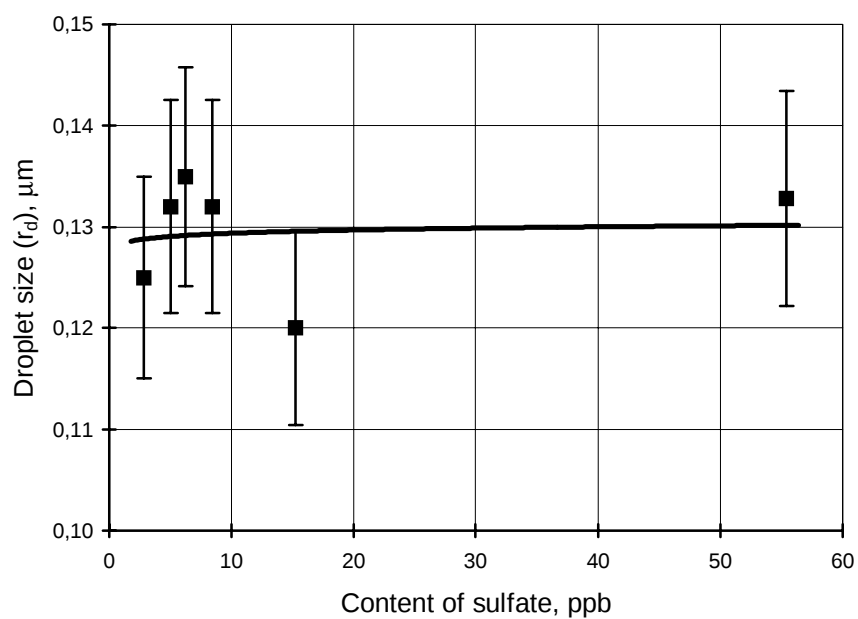


Figure 3-9
Droplet Size Vs. Content of Sulfate in the Inlet Steam with OT ($y = 0.75\%$)

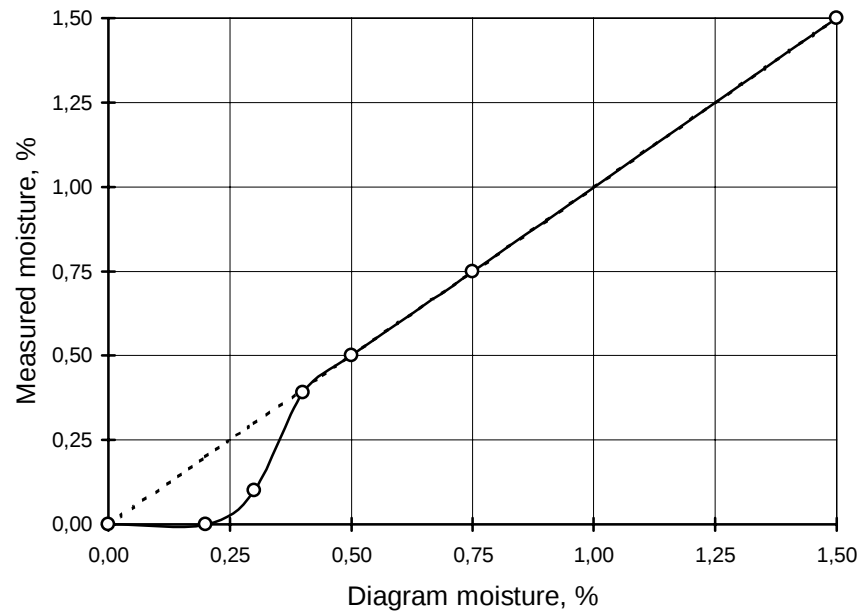


Figure 3-10
Measured Moisture Vs. Diagram Moisture

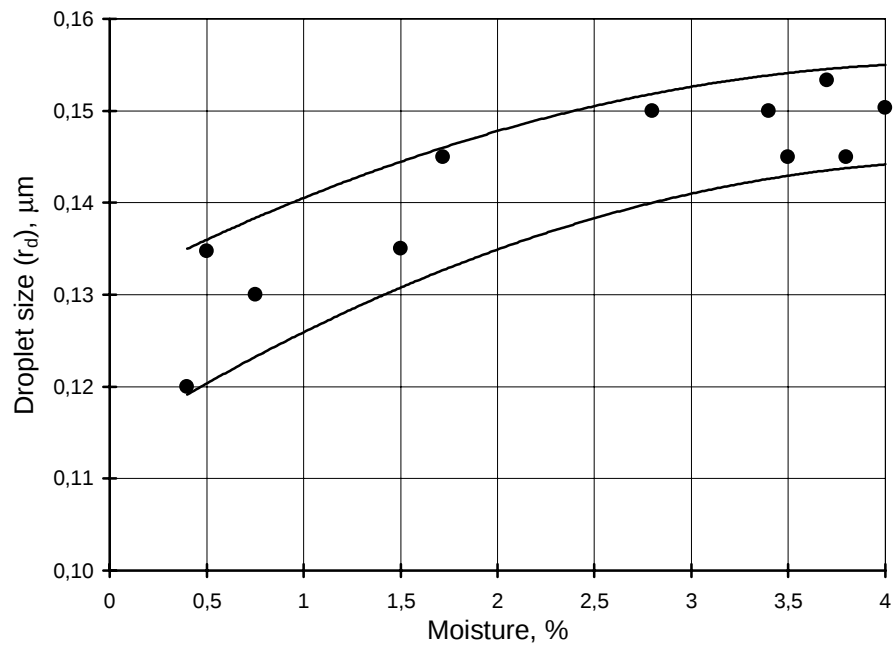


Figure 3-11
Droplet Size (Radius) Vs. Moisture

In summary, on the basis of the droplet size and moisture measurements the following conclusions can be made:

- At constant turbine operating parameters (p_0 , T_0 , p_c , G , f), a change from PT3.0 to OT, and different initial levels of chloride and sulfate (*ca.* 2 – 70 ppb), does not result in a change of the size of the early condensate droplets generated during steam expansion in the turbine.
- Increase in the steam moisture at the exit of the turbine from 0.5 to 4.0% results in increase in droplet size r_d from 0.13 to 0.15 μm .

Effect of Steam Chemistry and Impurity Level on the Distribution of Temperatures and the Formation of Liquid Films

Blades and disks of turbine stages operating in the phase transition zone are those usually affected by corrosion. The accompanying corrosion fatigue or stress corrosion cracking often result in steam turbine failures. These phenomena occur when corrosive substances are present on the metal surface.

The experiments performed have lead to the following conclusions:

- Moisture in real turbines is generated immediately upon crossing the phase transition line $x = 1$, i.e. before the commonly known Wilson Line⁽⁴⁾.
- The concentration of corrosive impurities in the early condensate is not “corrosive” enough⁽⁵⁾ to drive the corrosion mechanisms.
- The early condensate droplets can generate liquid films on turbine stage elements by impingement and precipitation due to turbulent pulsations of the gas phase adjacent to the blade surface.
- Liquid films on the metal surface in the phase transition region are not continuous, but exist as separate lens shapes and as liquid streams.

Two models of generation of highly concentrated solutions on metal surface seem possible:

- Dissolution of deposits on blade surfaces by the films formed during condensation.
- Concentration of impurities in the liquid films due to heat-and-mass transfer and by evaporation of a portion of the liquid from the film.

Concentration can also occur in the crevices associated with active corrosion mechanisms or at blade attachment regions.

One of the key objectives during the study of failures of turbine stage elements operating in the phase transition zone is a detailed experimental study of liquid film formation, measurement of temperature of each component (gas/liquid phase and solid surface), and their interrelation with the concentration of the chemical compounds, which may cause corrosion.

The converging-diverging nozzle section and the preinstalled turbine have been used in this study. The detailed description of the test rig and systems of measurement are given in Section 2.

The tests were performed with PT3.0 and OT treatments with different chloride and sulfate concentrations at the turbine inlet. But during the tests it was found that a lower pH in the feedwater when ammonia feed was reduced (no addition of oxygen) resulted in a major change in the liquid film thickness and the temperature parameters on the channel surface.

A similar situation was also found when oxygen was added to the inlet steam with PT3.0. Thus, to study the separate effects of ammonia and oxygen on film thickness and steam supercooling, two additional chemistries were considered and analyzed: (a) lower ammonia levels (pH < 8.8) termed no additions (NA) and (b) PT3.0 chemistry with addition of oxygen into the inlet steam (PT3.0-DO). The PT3.0 chemistry is as defined previously and has feedwater pH of 9.0 ± 0.2 .

These results were compared with the previous study.

Figure 3-12 shows the dependence of the relative liquid film thickness $\bar{\delta}_f$ with chemistry over the monitored channel section. The results are shown to relative to the liquid film thickness for PT3.0 representing 1.

The value $\bar{\delta}_f$ is conventional to some extent, and is expressed as:

$$\bar{\delta}_f = \frac{\bar{\delta}_{f,i}}{\bar{\delta}_{f,o}} \quad (\text{eq. 3-17})$$

where $\bar{\delta}_{f,i}$ is the averaged liquid film thickness over the channel section length at the given chemistry:

$$\bar{\delta}_{f,i} = \frac{\sum \delta_f}{m} \quad (\text{eq. 3-18})$$

where $\sum \delta_f$ is the sum of the absolute film thickness values measured with “m” gauges installed in the channel section.

The subscript “o” in $\bar{\delta}_{f,o}$ shows, that the averaging of the liquid film thickness was performed at the PT3.0 with no impurities added, and both $\bar{\delta}_{f,o}$ and PT 3.0 are base film thickness and chemistry respectively. Therefore, $\bar{\delta}_f$ with the PT3.0 is unity.

As an example, Figure 3-13 shows the absolute values of the average liquid film thickness with the PT3.0 (no impurities). Five film thickness gauges continuously detected changes in the liquid film thickness along the channel length. Note that for all conditions considered the steam parameters at the channel inlet were kept constant ($p_1 = 0.048$ MPa (7 psi), $y_0 = 0.75\%$).

Analysis of the data shown in Figure 3-12 shows that:

- $\bar{\delta}_f$ is lower when less ammonia is added (PT3.0 vs. NA and OT).

- $\bar{\delta}_f$ is significantly lower when oxygen is added to steam with ammonia remaining constant in the feedwater (PT3.0 vs. PT3.0-DO).
- $\bar{\delta}_f$ is not changed significantly when oxygen is added to steam with less ammonia present (NA vs. OT).

Similar dependencies were also produced in the previous studies⁽¹⁾ (Figure 3-14) where the liquid films were measured on an actual nozzle blade. Comparison of this previous data with the current data (Figure 3-12) shows fairly good agreement. Note that in the previous tests a more significant effect of chloride and sulfate on the liquid film thickness was observed. In the current tests this effect was insignificant.

It should be remembered, that the current tests were slightly different than those conducted in the previous study. This difference was primarily related to the studied equipment and the gas dynamic parameters (rate of turbulence, supercooling, velocity vectors of carrying and discrete phases etc.) The liquid films in the previous study were measured on actual turbine nozzle blades, whereas in the current study they were measured on a plate within a nozzle fed with steam from a turbine. The similarity of results is technically pleasing.

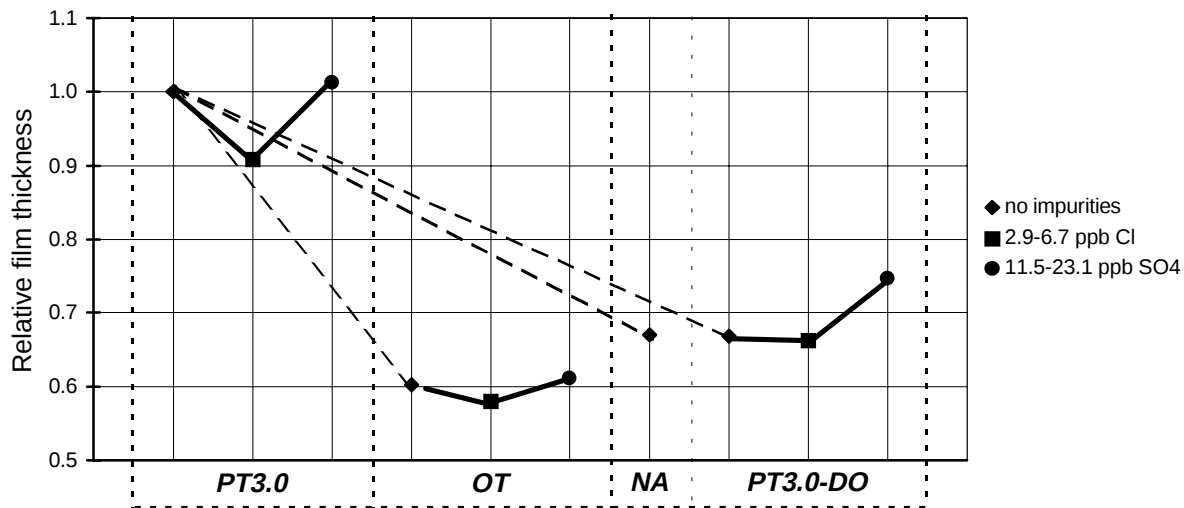


Figure 3-12
Relative Film Thickness on the Channel Profile Vs. Chemistry and Level of Impurities

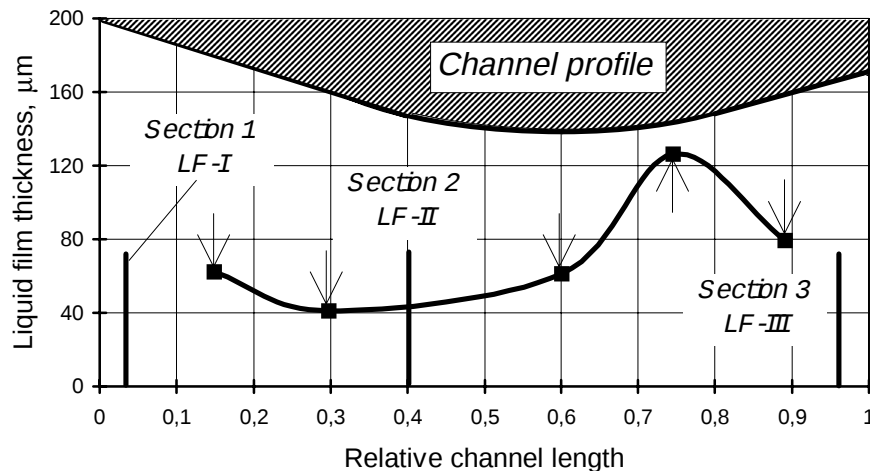
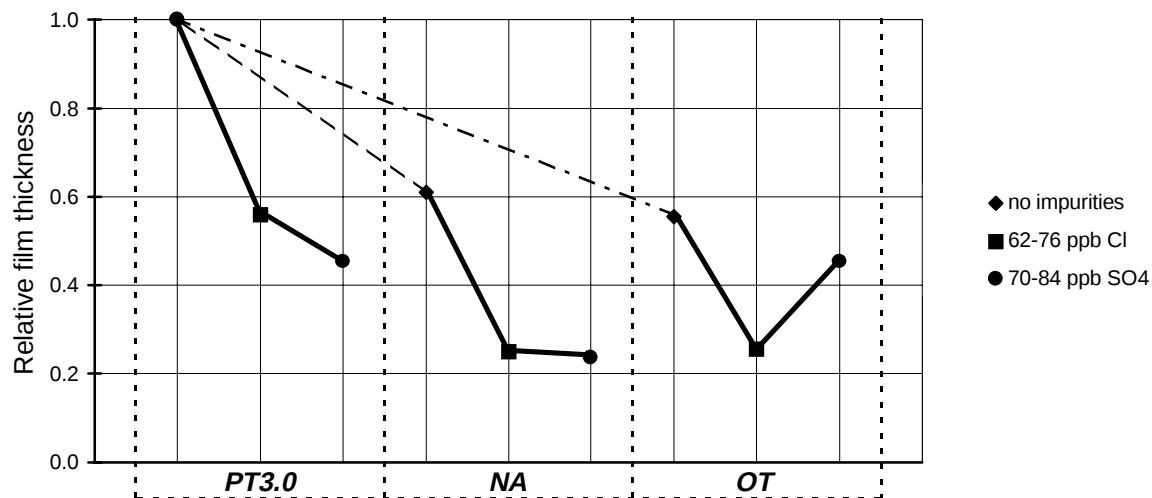


Figure 3-13
Film Thickness Along the Channel Profile with PT3.0
 $(\epsilon_1 = 0.82, y_0 = 0.75, Re_1 = 2.7 \times 10^5)$. Arrows indicate location of film thickness gauges.



Source: Reference 1

Figure 3-14
Relative Film Thickness on the Nozzle Blade Vs. Chemistry and Level of Impurities in Previous Tests⁽¹⁾

Two basic reasons for the changes in the liquid film thickness with chemistry may be proposed:

- Change in surface tension of liquid droplets formed during condensation and surface wettability, where precipitation occurs. For example, a change in surface tension of the stream may result in a change in the edge wetting angle, resulting in a change of the liquid film thickness. The same may be applied to wettability.

- It is known that the process of steam condensation changes with addition of certain chemicals into steam, with an associated shifting of the initiation of steam condensation upstream or downstream. This, in turn, will change the rate of precipitation on the channel surface and the measured film thickness even with the same inlet steam parameters.

Another mechanism can also be suggested. This relates to the effect of the chemistry on the charge density of the moist medium prior to precipitation on the metal surface. Measurement of the charge density and of the charge (potential) associated with the liquid films as a function of steam chemistry, is being addressed in the next phase of this work.

All these factors will take place simultaneously. The current tests have not provided the answer on the rate of “interaction” between the factors. The surface tension and wettability are currently being measured in other EPRI projects.

With regards to the second reason, tests on the change in the steam supercooling at the channel inlet were performed. Stagnation temperatures determined from the equilibrium Mollier Diagram were compared to measured temperatures at the same point.

Previous studies⁽⁶⁾ showed that one of the reasons for the reduction of stagnation temperature was pulsation processes. This effect is more obvious near the saturation line, when an additional fluctuation mechanism associated with phase transitions comes into force. This mechanism contributes to the pulsation process. In particular, it causes intensification of pulsations of total and static pressures and thermodynamic temperatures. This process is accompanied by phase transitions, and unstable nuclei generated within the outlet sections of the second stage cascade which are evaporated and are generated again. This results in intensive interphase heat-and-mass transfer.

Figure 3-15 shows current test results of supercooling $\Delta T_1 = T_{1, \text{diagr}} - T_1$, where $T_{1, \text{diagr}}$ is the stagnation temperature determined from the equilibrium Mollier Diagram; T_1 is the measured stagnation temperature in the flow nucleus in the same section.

Comparison of the data presented in Figures 3-12 and 3-15 suggests that relative film thickness is related with supercooling. The steam supercooling with the PT3.0 does not exceed 1 °C (1.8 °F), while it reaches -2 °C (-3.6 °F) with the OT and the PT3.0-DO, and feed of impurities increases the supercooling to -4 °C (-7.2 °F).

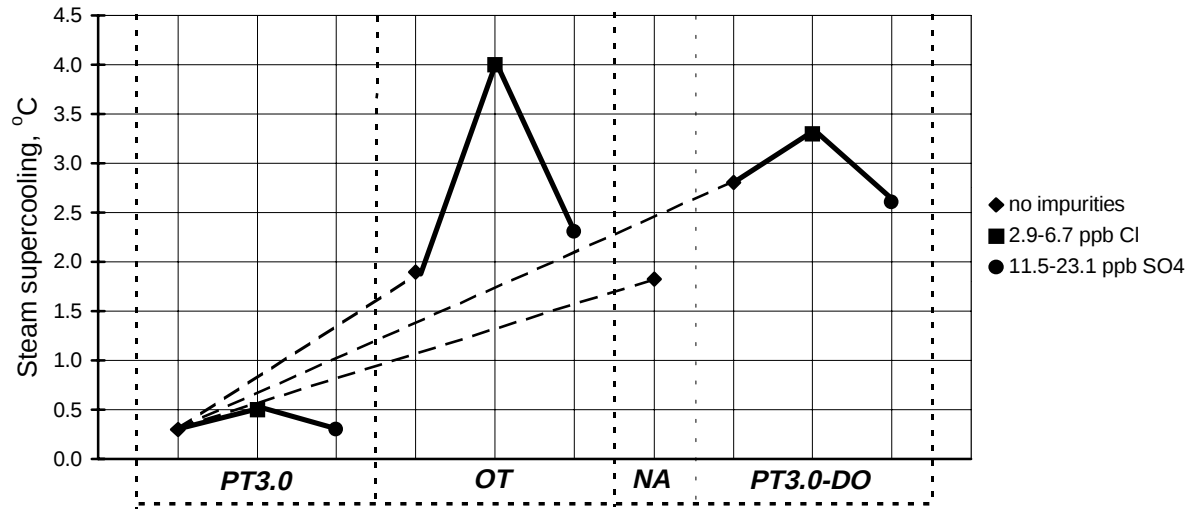


Figure 3-15
Steam Supercooling at the Channel Inlet Vs. Chemistry and Level of Impurities

Effect of Oxygen on Steam Supercooling and Liquid Film Thickness

This subsection considers how the addition of oxygen influences the temperatures and film thickness monitored during the tests. Figure 3-16 presents ΔT_1 and $\bar{\delta}_f$ curves with and without the addition of oxygen.

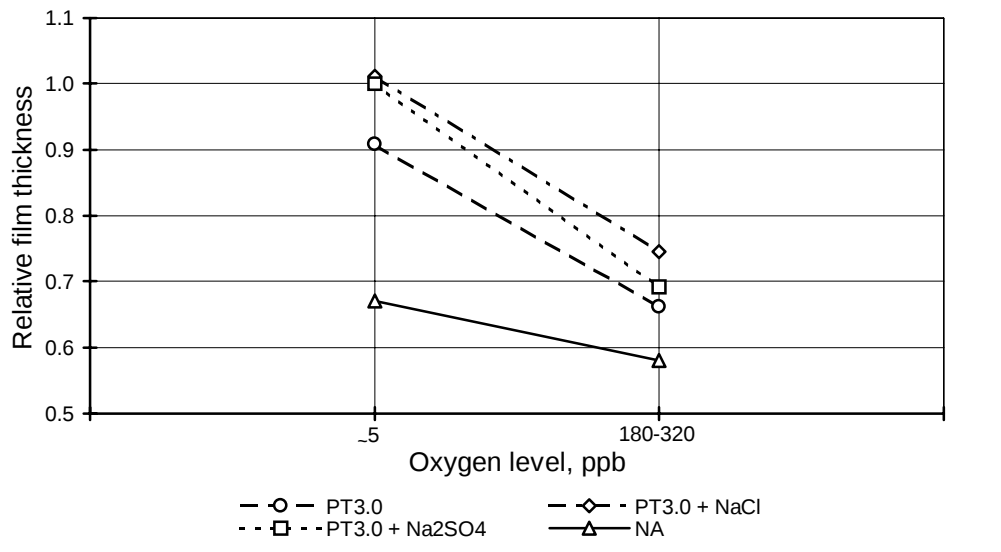
These data show, that addition of oxygen changes significantly the steam supercooling at the channel inlet and the liquid film thickness. If at the PT3.0 chemistry ΔT_1 is close to zero (Figure 3-16, b), then at the PT3.0-DO the situation is different: supercooling reaches 3 °C (5.4 °F), and the addition of chloride and sulfate causes insignificant change of ΔT_1 which ranges from 2.6 to 3.1 °C (4.7 – 5.6 °F). This exerts an influence on the initiation of condensation: change in the relative film thickness testifies this. Note that even a -3 °C (5.4 °F) variation in supercooling at the channel inlet results in a marked reduction of the relative film thickness from 1 (no oxygen) to 0.7 (feed of oxygen).

Experiments on the effect of oxygen addition on the temperature parameters and the liquid film thickness along the channel were also conducted with PT3.0 + Na₂SO₄ (SO₄ ~ 35 ppb) and PT3.0-DO + Na₂SO₄ (SO₄ ~ 35 ppb, DO ~ 300 ppb). The inlet steam parameters were the same. The test results are shown in Figure 3-17.

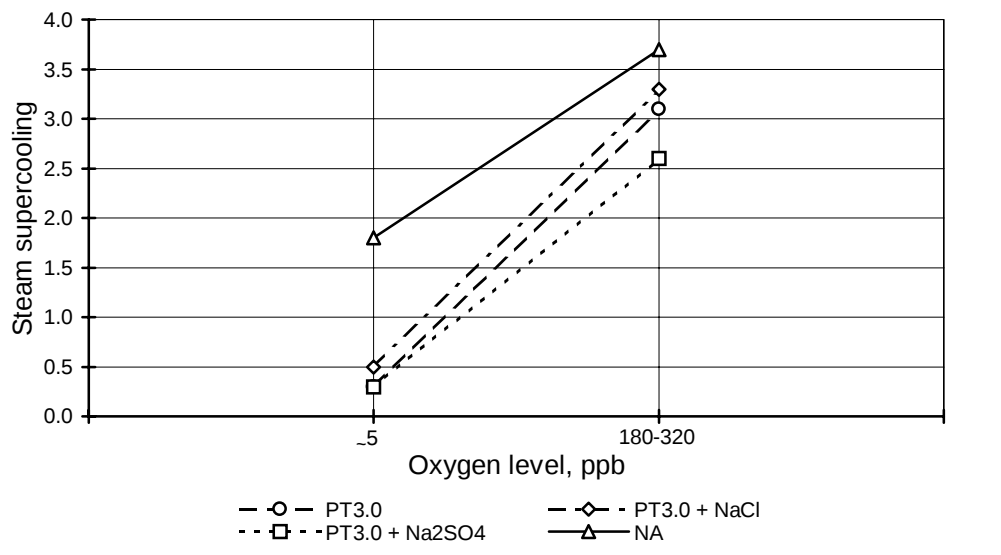
Here $\Delta T_{ch} = T_{ch} - T_s$, where T_{ch} is the fluid temperature measured directly on the channel surface; T_s is the saturation temperature determined from the static pressure in the given section. The plots in Figure 3-17 show, that the channel geometry exerts an influence on $\bar{\delta}_f$ and ΔT_{ch} . Acceleration of flow in the converging section results in approximately 20 μm reduction in the film thickness for both chemistries. The pattern is opposite in the diverging section of the nozzle.

Addition of oxygen resulted in noticeable increase in ΔT_{ch} along the channel (Figure 3-17). This change in supercooling lead to a change in a rate of surface precipitation with the moisture formed. This, in turn, resulted in a decrease in the liquid film thickness.

These results are in agreement with those shown in Figure 3-16: increase of oxygen decreases the liquid film thickness and increases the steam supercooling.



a)



b)

Figure 3-16
Relative Film Thickness (a) and Steam Supercooling (b) Vs. Oxygen

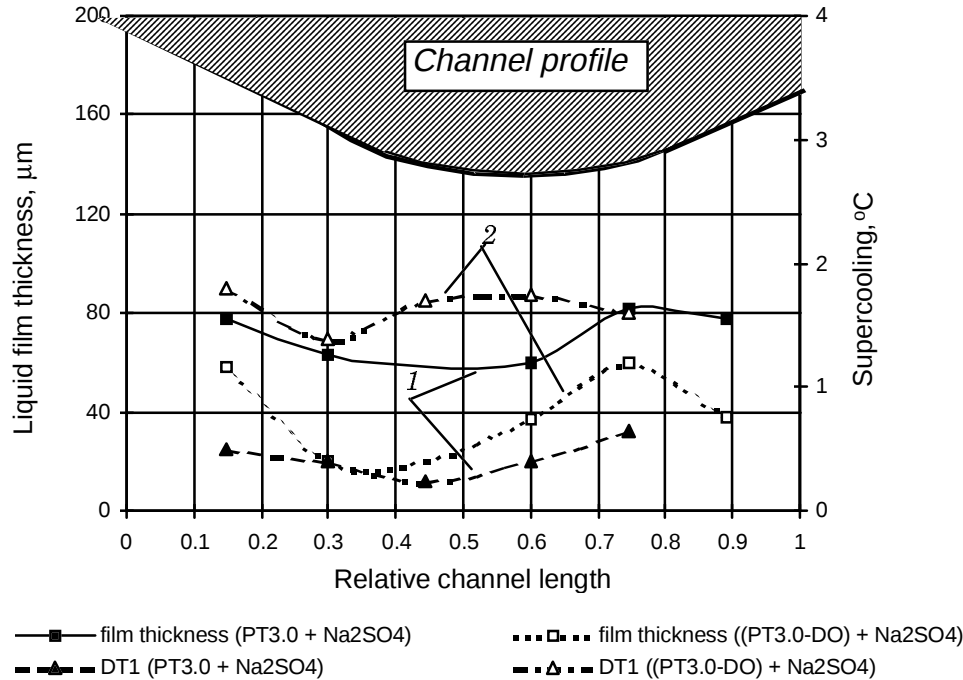


Figure 3-17

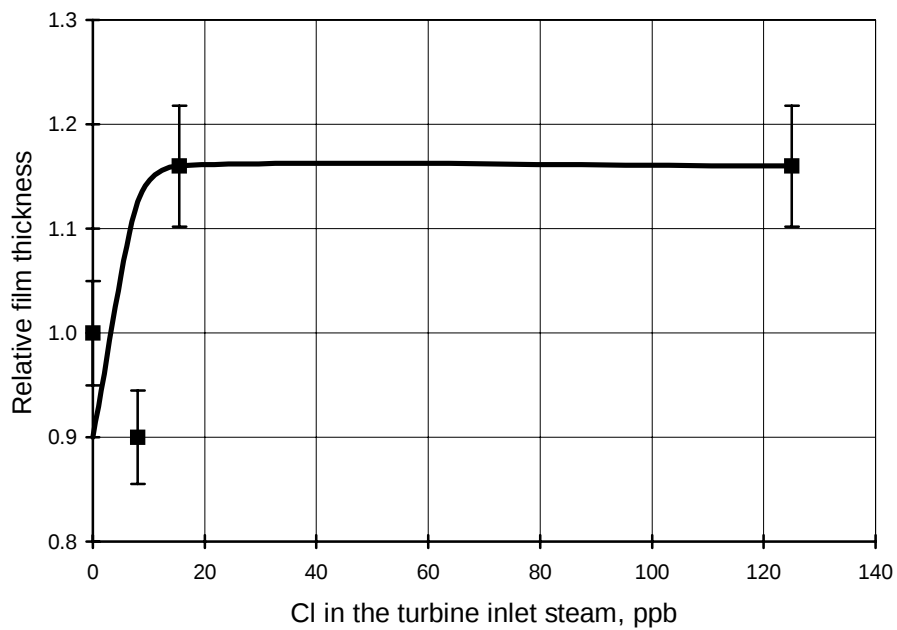
Film Thickness and Steam Supercooling Along the Channel Profile with no Oxygen (1) and with Oxygen (2) in Steam

Effect of Chloride and Sulfate Levels in Inlet Steam on Liquid Film Thickness and Steam Supercooling

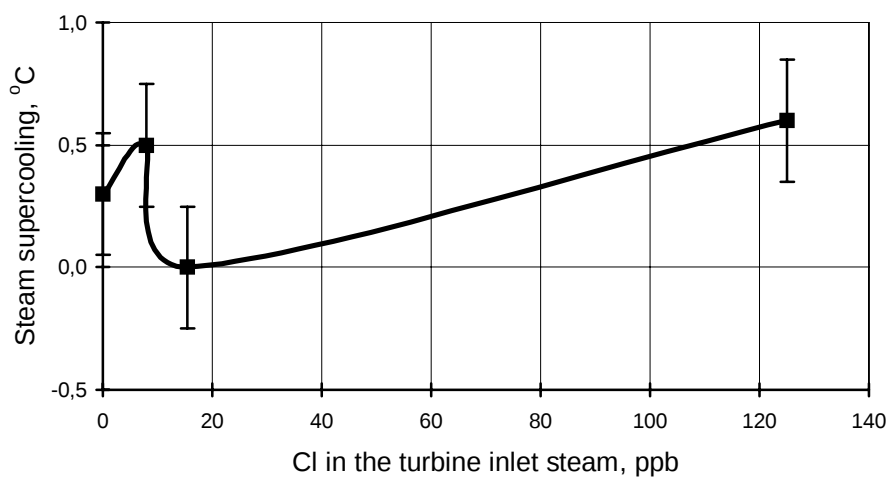
PT3.0 Chemistry

The data on the liquid film thickness and the steam supercooling vs. Inlet chloride and sulfate levels are presented in Figures 3-18 and 3-19. Analysis of the curves (Figure 3-18) shows, that with minimum chloride at the turbine inlet (2 ppb) the relative film thickness $\bar{\delta}_f$ is 1.0 (Figure 3-18, a). A slight increase in chloride level (to 6.7 ppb) resulted in some reduction of $\bar{\delta}_f$, but at Cl = 15.5 ppb the relative film thickness increased to 1.18. Further increase in chloride level to 125.6 ppb had almost no effect on $\bar{\delta}_f$. Analysis of the steam supercooling data (Figure 3-18, b) shows, that higher ΔT_1 values correspond to lower $\bar{\delta}_f$, but absolute ΔT_1 values are small and do not exceed 1 °C (1.8 °F.)

The similar pattern was observed with the addition of sulfate (Figure 3-19), but here a reduction of $\bar{\delta}_f$ with small sulfate levels was not observed. The increase in sulfate level up to 35 ppb resulted in monotonous slight increase in the relative film thickness: it was 1.1 with SO₄ = 35.5 ppb. Further increase in sulfate level did not result in a further increase of $\bar{\delta}_f$, and with SO₄ = 75 ppb it decreased. As with chlorides, steam supercooling was insignificant ($\Delta T_1 < 0.5$ °C (0.9 °F)).

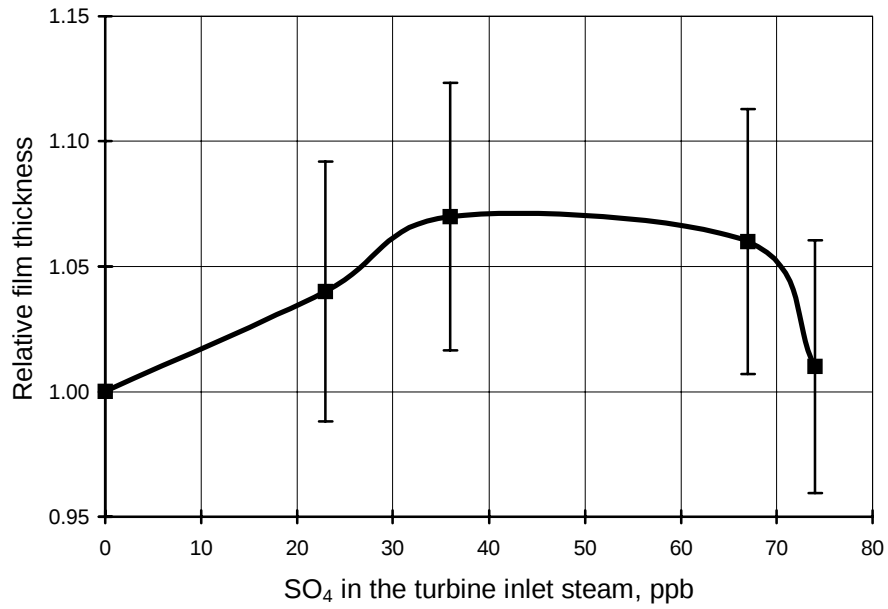


a)

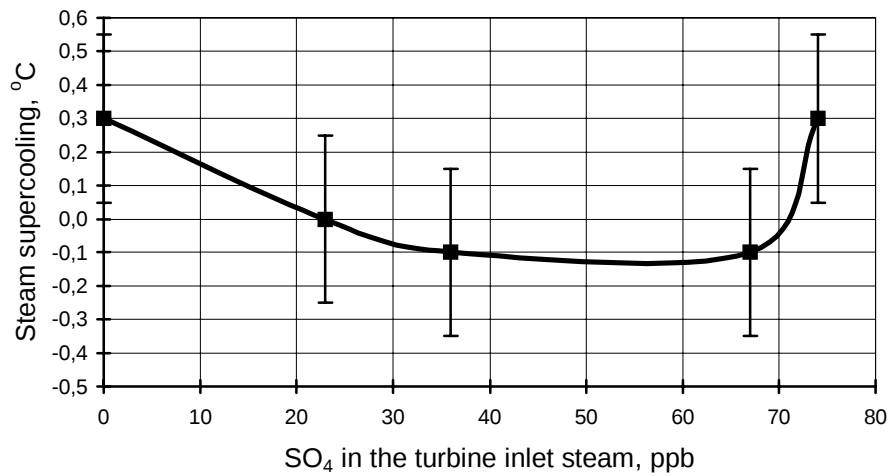


b)

Figure 3-18
Relative Film Thickness (a) and Steam Supercooling (b) at the Channel Inlet Vs. Chloride with PT3.0



a)



b)

Figure 3-19
Relative Film Thickness (a) and Steam Supercooling (b) at the Channel Inlet Vs. Sulfate with PT3.0

OT Chemistry

The test results with OT are shown in Figures 3-20 and 3-21. With this chemistry, oxygen was added into the inlet steam (180 – 350 ppb), and pH of the steam was in a range of 8.4 – 8.6.

Analysis of the data shows that

- Reduction of ammonia level[‡] in steam resulted in a decrease in the relative film thickness $\bar{\delta}_f$ (Figures 3-20, a and 3-21, a) and increase in the steam supercooling ΔT_1 (Figures 3-20, b and 3-21, b).
- Feed of oxygen resulted in further decrease in the relative film thickness and maximum steam supercooling (Figures 3-12 and 3-15).
- Addition of chloride and sulfate into the steam slightly reduced the steam supercooling and increased the relative film thickness.

PT3.0-DO Chemistry

As was mentioned above, to define the effect of oxygen and ammonia on the relative film thickness and the steam supercooling, additional PT3.0 tests with addition of oxygen were performed. The oxygen level during these tests was 180 – 350 ppb. The test results are shown in Figures 3-22 and 3-23.

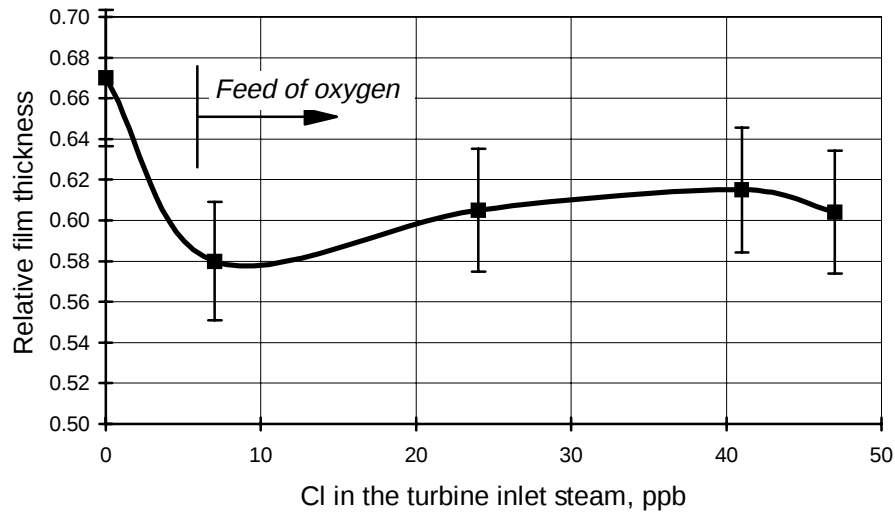
Comparison of the curves shown in Figures 3-22 and 3-23 with those in Figures 3-20 and 3-21 shows, that ammonia + oxygen (all other conditions being the same) resulted in:

- Noticeable reduction (by ~ 2 °C (3.6 °F) of the steam supercooling at the channel inlet.
- Increase in the relative film thickness compared with OT (Figures 3-12 and 3-16).

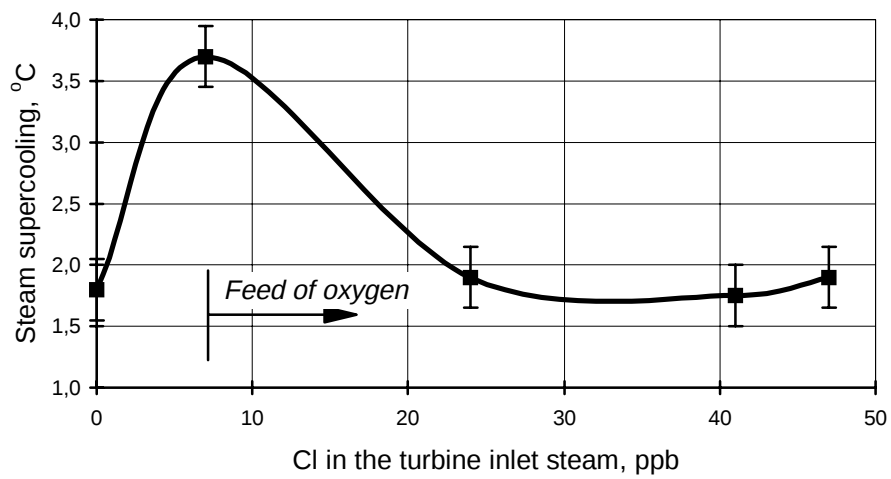
These dependencies are valid with both chloride and sulfate addition.

During the tests the effect of oxygen was observed on the following flow parameters: the liquid film thickness and the steam supercooling at the channel inlet. The liquid film thickness decreased, and the supercooling increased when oxygen was added. At the same time reduction was found in the concentration of chloride and sulfate in the early condensate and the liquid films with OT compared with PT3.0. But at low levels of impurities in the turbine inlet steam, the ratio between the impurity levels in the liquid film and the early condensate with OT was higher than with PT3.0.

[‡] During the first stage of the tests $\bar{\delta}_f$ and ΔT_1 were measured with reduced ammonia levels (to compare with PT3.0) with no oxygen added.

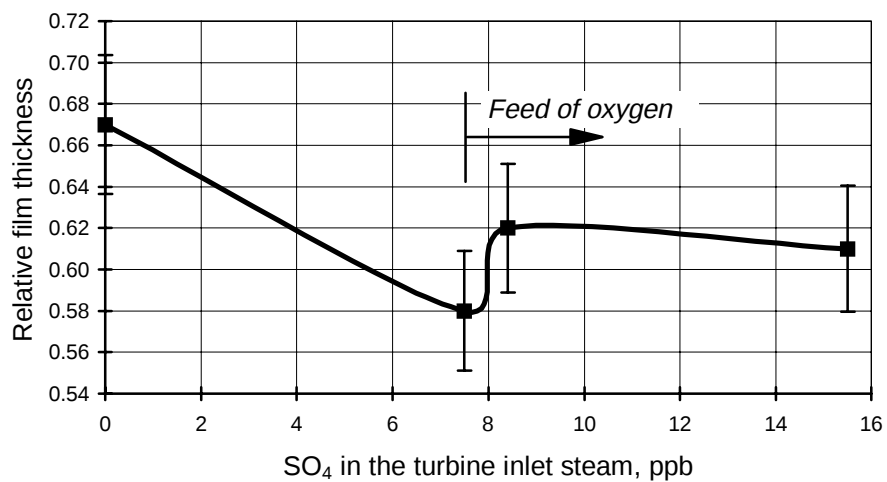


a)

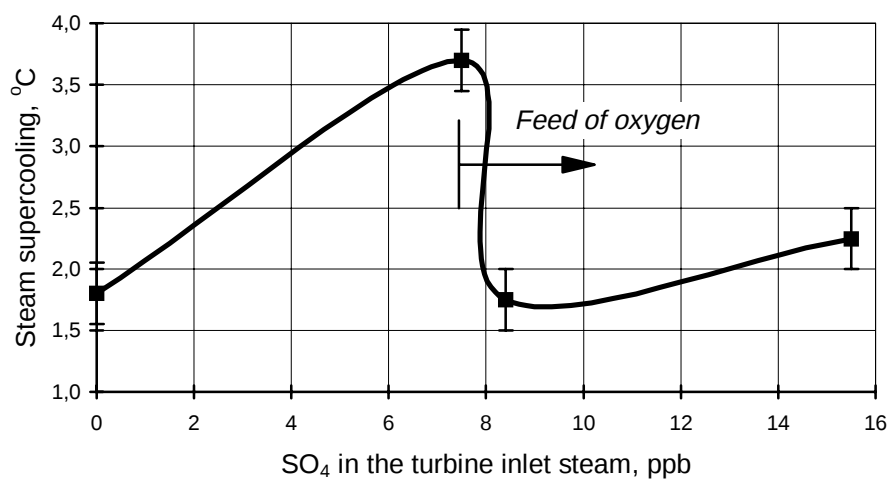


b)

Figure 3-20
Relative Film Thickness (a) and Steam Supercooling (b) at the Channel Inlet vs. Chloride with OT

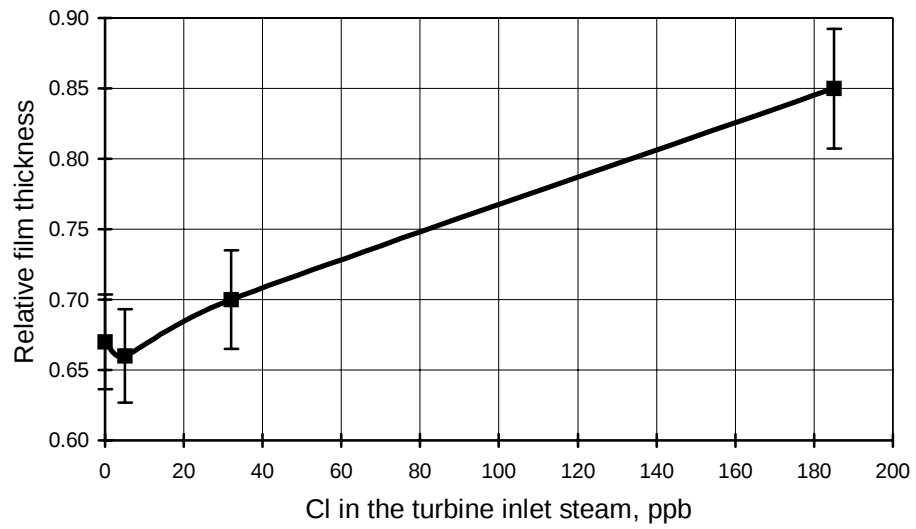


a)

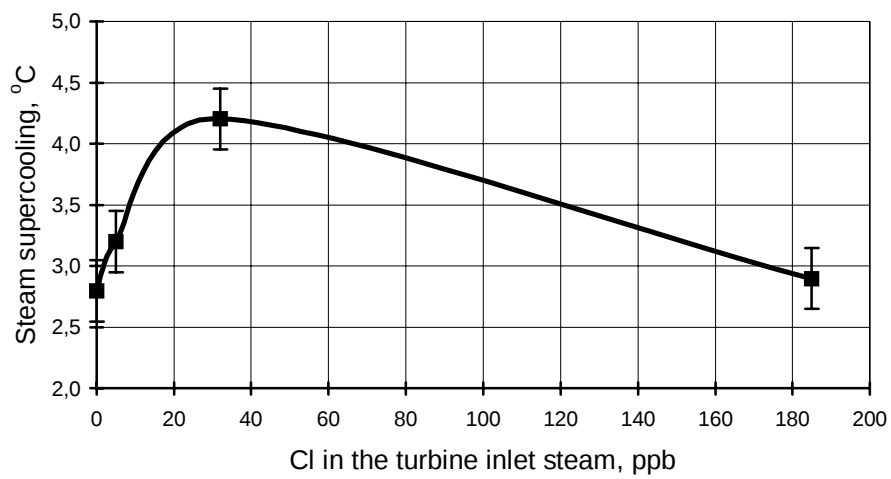


b)

Figure 3-21
Relative Film Thickness (a) and Steam Supercooling (b) at the Channel Inlet vs. Sulfate with OT

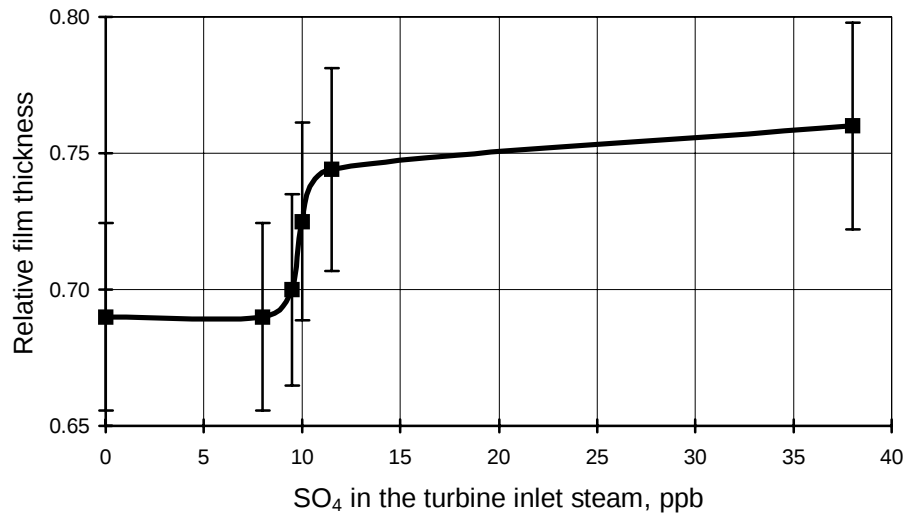


a)

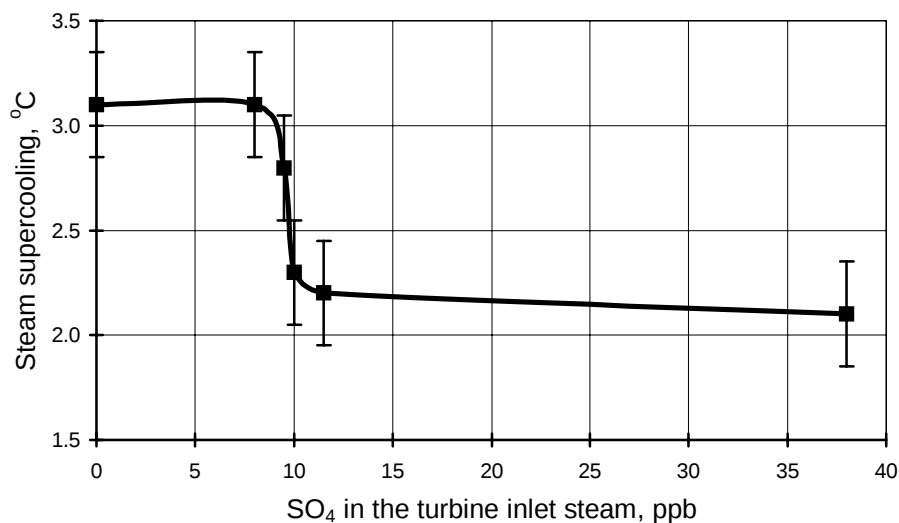


b)

Figure 3-22
Relative Film Thickness (a) and Steam Supercooling (b) at the Channel Inlet Vs. Chloride with PT3.0-DO



a)



b)

Figure 3-23
Relative Film Thickness (a) and Steam Supercooling (b) at the Channel Inlet Vs. Sulfate with PT3.0-DO

One of the possible reasons for this might be that iron corrosion products in the early condensate are not only in dissolved state, but also as solid particles, e.g. colloids.

It is known⁽⁷⁾ that any heterogeneous system is characterized by potential difference between phases of this system and that there are hydroxyl groups present on the surface of oxides in the electrolyte solution. This results in electric charge produced on the surface of corrosion products; the value depends on the composition of the impurities.

An adsorption of oxygen molecules on oxide surfaces is possible with OT, which may change magnitude of the particle charge. It is known that presence of oxygen affects a shift in the point of zero charge, i.e. pH value, when the surface charge is zero, to higher pH values. Some studies⁽⁸⁾ have shown that the point of zero charge with OT is around 7.5 – 8.0, and with AVT, 5.8 – 6.8.

Therefore it may be assumed that the above-mentioned factors could result in an increase in the rate of flow supercooling and in a delay of the condensation process with OT, which, in turn, may reduce the film thickness.

Since the heat released from the wall to the liquid film is the same, then the relative portion of evaporated liquid will be higher resulting in an increased “LF/EC” concentration ratio of chloride and sulfate with OT compared with PT3.0. This also may be the reason why there are different levels of impurities in the liquid films extracted from Section No. 2 and Section No. 3.

Unfortunately, the effect of these factors on the pulsation components of the adjacent steam flow against the wall, which is one of the basic mechanisms for fine droplet precipitation, is unknown. Therefore, for a better understanding of the mechanism of concentration of impurities in the liquid film on turbine flowpath surfaces, the next phase of the work will perform studies on the measurement of particle charge and pulsation components of the flow velocity.

In summary, on the basis of the droplet size and moisture measurements the following conclusions can be made:

- The maximum liquid film thickness is measured with PT3.0.
- A decrease in the ammonia level in the inlet steam results in a reduction of the liquid film thickness.
- Feed of oxygen in to the steam with PT3.0 results in a reduction of the liquid film thickness.
- At low levels of chloride and sulfate in the inlet steam (<10 ppb) with OT, the maximum supercooling and maximum concentration ratio of impurities in the liquid film related to the early condensate are found.

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4

CONCLUSIONS

During the tests using a model turbine, the effect of two chemistries – phosphate treatment (PT3.0) and oxygenated treatment (OT) with different initial level of chloride and sulfate in the inlet steam – was studied on the following parameters:

- The concentration of impurities in early condensate and liquid films
- The size of the early condensate droplets formed during steam expansion in the turbine.
- Thickness and temperature of the liquid films on the metal surface.

Analysis of the experimental results leads to the following conclusions:

- Concentration of corrosive impurities in the liquid films formed on the surface of blades and disks can be an order of magnitude higher than that in the EC.
- For the studied chemistries, an increase in the level of chloride and sulfate in the inlet steam resulted in an increase in the concentration of these impurities in the early condensate and the liquid films.
- Use of PT3.0 chemistry produces the highest concentration (and concentration ratio) of corrosive impurities, and the use of OT results in the lowest level (and concentration ratio) of chloride and sulfate in the early condensate and the liquid films.
- An elevated sulfate in the turbine inlet steam results in increased contamination of the early condensate and the liquid films with chloride.
- The pH of the early condensate and the liquid films is about. 2 – 3 pH units lower than the pH of the turbine inlet steam.
- Oxygen does not concentrate in the early condensate or the liquid films.
- At constant turbine operating parameters (p_0 , T_0 , p_c , G , f), a change from PT3.0 to OT, and different initial levels of chloride and sulfate (about 2 – 70 ppb), does not result in a change in the size of the early condensate droplets generated during steam expansion in the turbine.
- Increase in the steam moisture at the exit of the turbine from 0.5 to 4.0% results in an increase in droplet size (r_d) from 0.13 to 0.15 μm .
- Maximum liquid film thickness is measured with PT3.0.
- Decrease in ammonia level in the inlet steam results in a reduction of the liquid film thickness.
- Feed of oxygen in to the steam with PT3.0 results in a reduction of the liquid film thickness.

Conclusions

- At low levels of chloride and sulfate in the inlet steam (<10 ppb) with OT the maximum supercooling and maximum concentration ratio of impurities in the liquid film as compared to the early condensate are found.

A

APPENDIX

Detailed test results are presented in the appendix. Table A-1 gives the data on inlet steam parameters (pressures and temperatures), Table A-2 – inlet steam chemistry; Table A-3 – liquid film thickness along the test channel; Table A-4 – fluid temperature on wall surface; Table A-5 – temperature of wall surface; and Table A-6 – static pressure along the test channel.

Table A-1
Inlet Steam Parameters (Pressures and Temperatures)

No.	Chemistry	Turbine inlet steam parameters		Nozzle inlet steam parameters			
		p_0 , MPa	T_0 , °C	y_n , %	p_1 , MPa	p_{1stat} , MPa	T_{1stat} , °C
1	PT3.0	0.112	120	0.90	0.0469	0.0424	75.3
2	PT3.0	0.112	124	0.75	0.0481	0.0444	79.2
3	PT3.0	0.112	124	0.75	0.0484	0.0441	78.2
4	PT3.0	0.112	124	0.75	0.0475	0.0438	77.6
5	PT3.0	0.112	120	0.75	0.0475	0.0435	77.6
6	PT3.0	0.112	120	0.75	0.0475	0.0435	78.2
7	OT	0.112	118	0.75	0.0489	0.0454	75.3
8	OT	0.112	118	0.76	0.0489	0.0454	75.0
9	OT	0.112	120	0.77	0.0482	0.0454	76.6
10	OT	0.112	119	0.8	0.0482	0.0452	76.7
11	OT	0.112	118	0.87	0.0484	0.0449	75.3
12	OT	0.112	118	0.77	0.0482	0.0452	76.1
13	PT3.0	0.112	120	0.90	0.048	0.044	76.4
14	PT3.0	0.112	122	0.60	0.0473	0.0431	73.9
15	PT3.0-DO	0.112	119	0.78	0.0479	0.0436	74.7
16	PT3.0-DO	0.112	118	0.75	0.047	0.0427	73.7
17	PT3.0-DO	0.112	118	0.82	0.0472	0.0435	73.2
18	PT3.0-DO	0.112	119	0.73	0.0477	0.0432	74.4
19	PT3.0-DO	0.112	122	0.70	0.0471	0.0424	73.7
20	PT3.0-DO	0.112	121	0.80	0.0466	0.0419	74.1
21	PT3.0-DO	0.112	120	0.58	0.0489	0.0449	78.2

Table A-1
Inlet Steam Parameters (Pressures and Temperatures)

No.	Chemistry	Turbine inlet steam parameters		Nozzle inlet steam parameters			
		p_0 , MPa	T_0 , °C	y_n , %	p_1 , MPa	p_{1stat} , MPa	T_{1stat} , °C
22	PT3.0-DO	0.112	120	0.75	0.0469	0.0421	74.1
23	PT3.0-DO	0.112	122	0.70	0.0469	0.0419	73.5
24	NA	0.112	119	0.77	0.0482	0.0454	76.7

Table A-2
Inlet Steam Chemistry

No.	Chemistry	Cl, ppb	SO ₄ , ppb	pH	Na, ppb	sc, μ S/ cm	cc μ S/ cm	DO ppb
1	PT3.0	2.0	2.0	9.3	0.73	2.63	0.44	<5
2	PT3.0	6.7	5.1	9.2	10.9	3.73	0.60	<5
3	PT3.0	15.5	6.2	9.2	17.8	3.63	0.95	<5
4	PT3.0	2.0	23.1	9.3	32.4	3.23	0.56	<5
5	PT3.0	2.0	35.5	9.2	41.2	3.26	0.58	<5
6	PT3.0	2.0	66.9	9.2	79.8	3.61	0.59	<5
7	OT	7.5	6.2	8.5	2.7	1.99	0.52	290
8	OT	6.7	7.0	8.7	2.8	1.83	0.63	210
9	OT	24.0	5.0	8.6	23.5	1.97	0.76	250
10	OT	29.1	8.4	8.6	26.9	2.04	0.73	230
11	OT	41.3	2.0	8.5	32.4	1.99	0.51	180
12	OT	4.0	15.2	8.6	5.2	1.96	0.56	260
13	PT3.0	13.7	11.7	9.2	19.3	3.88	0.81	<5
14	PT3.0	6.9	74.2	9.4	67.8	5.13	0.93	<5
15	PT3.0-DO	9.1	2.0	2.0	1.2	2.93	0.53	190
16	PT3.0-DO	2.9	2.0	9.1	1.9	3.03	0.61	270
17	PT3.0-DO	32.8	2.0	9.1	27.1	3.33	0.71	230
18	PT3.0-DO	184.1	12.3	9.2	148.9	6.23	1.21	260
19	PT3.0-DO	2.0	8.4	9.1	6.1	3.53	0.67	290
20	PT3.0-DO	2.0	9.6	9.1	13.2	3.36	0.59	210
21	PT3.0-DO	2.0	10.1	9.3	9.8	3.83	0.76	250
22	PT3.0-DO	2.0	11.5	9.2	12.9	3.68	0.73	280

Table A-2
Inlet Steam Chemistry

No.	Chemistry	Cl, ppb	SO ₄ , ppb	pH	Na, ppb	sc, μ S/ cm	cc μ S/ cm	DO ppb
23	PT3.0-DO	2.0	15.2	9.1	17.8	3.76	0.78	280
24	NA	5.4	2.8	8.6	1.8	1.7	0.49	<5

Table A-3
Liquid Film Thickness Along the Test Channel

No.	Chemistry	Liquid film thickness along the test channel, μm (figures below indicate section number along the channel)				
		1	2	4	5	6
1	PT3.0	76.9	27.9	47.9	81.3	46.1
2	PT3.0	66	39	59	119	77
3	PT3.0	67.1	49.2	69.2	131.3	111.4
4	PT3.0	59	43	59	129	95
5	PT3.0	60	43	59	130	105
6	PT3.0	61	48	64	124	97
7	OT	54	23	39	65	38
8	OT	51	23	40	64	37
9	OT	60	19	40	64	38
10	OT	63	20	44	60	42
11	OT	55	31	45	65	44
12	OT	63	21	42	61	39
13	PT3.0	62	41	61	126	79
14	PT3.0	77	64	65	85	84
15	PT3.0-DO	65	27	43	70	44
16	PT3.0-DO	63	29	45	63	45
17	PT3.0-DO	65	32	51	64	46
18	PT3.0-DO	71	43	71	75	55
19	PT3.0-DO	61	28	44	81	42
20	PT3.0-DO	61	29	45	74	42
21	PT3.0-DO	63	32	51	68	45

Table A-3
Liquid Film Thickness Along the Test Channel

No.	Chemistry	Liquid film thickness along the test channel, μm (figures below indicate section number along the channel)				
		1	2	4	5	6
22	PT3.0-DO	62	35	53	78	49
23	PT3.0-DO	62	28	45	79	42
24	NA	72	19	48	66	43

Table A-4
Fluid Temperature on Wall Surface

No.	Chemistry	Fluid temperature on wall surface, °C (figures below indicate section number along the channel)				
		1	2	3	4	5
1	PT3.0	76.4	76.7	72.9	72.2	72.3
2	PT3.0	75.8	76.7	72.2	74.5	73.7
3	PT3.0					
4	PT3.0	77.7	77.4	75.7	74.5	73.5
5	PT3.0	75.3	74.4	72.8	72.9	72.5
6	PT3.0	76.4	76.3	75.3	73.9	73.1
7	OT	76.6	77.1	70.3	75.7	75.0
8	OT	75.5	76.1	70.2	75.8	74.8
9	OT	76.0	75.4	71.9	74.7	73.7
10	OT	76.3	76.7	73.1	74.7	73.9
11	OT	75.4	76.6	69.4	75.8	74.8
12	OT	75.3	76.0	72.2	74.4	73.8
13	PT3.0	76.4	76.3	73.8	74.8	74.5
14	PT3.0	74.2	75.3	72.1	72.9	72.2
15	PT3.0-DO	76.0	76.1	73.1	73.8	73.5
16	PT3.0-DO	76.3	76.9	73.9	74.1	74.2
17	PT3.0-DO	76.6	77.4	74.7	75.1	74.7
18	PT3.0-DO	76.3	77.4	74.7	74.4	74.4
19	PT3.0-DO	76.7	77.3	73.9	73.5	72.9
20	PT3.0-DO	75.7	76.6	73.2	73.2	73.1
21	PT3.0-DO	75.8	75.3	73.9	74.7	74.7

Table A-4
Fluid Temperature on Wall Surface

No.	Chemistry	Fluid temperature on wall surface, °C (figures below indicate section number along the channel)				
		1	2	3	4	5
22	PT3.0-DO	76.7	77.3	73.9	73.7	71.9
23	PT3.0-DO	76.0	76.1	72.3	72.9	72.3
24	NA	75.0	75.3	70.3	74.4	73.4

Table A-5
Temperature of Wall Surface

No.	Chemistry	Metal temperature on wall surface, °C (figures below indicate section number along the channel)			
		1	2	3	6
1	PT3.0	74.4	71.8	70.2	74.8
2	PT3.0	75.1	73.8	71.2	78.7
3	PT3.0				
4	PT3.0	75.8	75.4	73.2	78.2
5	PT3.0	75.7	76.0	72.9	77.4
6	PT3.0	75.7	75.1	73.4	77.9
7	OT	78.2	71.8	68.7	74.5
8	OT	73.8	72.3	69.1	74.4
9	OT	74.7	73.1	71.0	76.6
10	OT	74.7	73.7	70.7	75.8
11	OT	73.1	71.6	68.8	74.5
12	OT	74.4	73.5	70.7	74.5
13	PT3.0	75.1	72.8	71.9	76.4
14	PT3.0	73.4	70.5	66.5	73.2
15	PT3.0-DO	72.5	70.5	65.8	75.4
16	PT3.0-DO	71.0	67.7	68.6	72.6
17	PT3.0-DO	71.6	69.7	69.4	73.4
18	PT3.0-DO	71.2	68.7	68.3	72.5
19	PT3.0-DO	71.8	70.3	69.3	73.7
20	PT3.0-DO	72.2	69.7	69.0	73.2
21	PT3.0-DO	73.1	70.9	67.1	73.5

Table A-5
Temperature of Wall Surface

No.	Chemistry	Metal temperature on wall surface, °C (figures below indicate section number along the channel)			
		1	2	3	6
22	PT3.0-DO	71.9	70.2	69.3	73.8
23	PT3.0-DO	71.5	69.9	69.0	74.5
24	NA	74.2	71.6	70.2	75.8

Table A-6
Static Pressure Along the Test Channel

No.	Chemistry	Static pressure along the test channel, MPa (figures below indicate section number along the channel)					
		1	2	3	4	5	6
1	PT3.0	0.0389	0.0389	0.0364	0.0349	0.0334	0.0331
2	PT3.0	0.0420	0.0424	0.0396	0.0386	0.0378	0.0378
3	PT3.0	0.0424	0.0416	0.0409	0.0394	0.0384	0.0389
4	PT3.0	0.0415	0.0408	0.0385	0.0380	0.0375	0.0375
5	PT3.0	0.0415	0.0410	0.0398	0.0383	0.0375	0.0378
6	PT3.0	0.0410	0.0403	0.0390	0.0383	0.0373	0.0373
7	OT	0.0434	0.0427	0.0407	0.0404	0.0394	0.0394
8	OT	0.0429	0.0424	0.0412	0.0399	0.0392	0.0392
9	OT	0.0432	0.0437	0.0412	0.0404	0.0402	0.0402
10	OT	0.0437	0.0442	0.0422	0.0412	0.0407	0.0407
11	OT	0.0434	0.0429	0.0419	0.0407	0.0397	0.0397
12	OT	0.0434	0.0437	0.0424	0.0407	0.0404	0.0402
13	PT3.0	0.0420	0.0413	0.0403	0.0388	0.0380	0.0383
14	PT3.0	0.0408	0.0403	0.0388	0.0366	0.0358	0.0363
15	PT3.0-DO	0.0409	0.0409	0.0389	0.0371	0.0361	0.0361
16	PT3.0-DO	0.0405	0.0405	0.0385	0.0370	0.0357	0.0357
17	PT3.0-DO	0.0405	0.0402	0.0385	0.0367	0.0355	0.0355
18	PT3.0-DO	0.0407	0.0402	0.0385	0.0365	0.0355	0.0355
19	PT3.0-DO	0.0389	0.0381	0.0364	0.0346	0.0334	0.0331
20	PT3.0-DO	0.0386	0.0381	0.0361	0.0341	0.0331	0.0331
21	PT3.0-DO	0.0427	0.0422	0.0407	0.0387	0.0374	0.0372

Table A-6
Static Pressure Along the Test Channel

No.	Chemistry	Static pressure along the test channel, MPa (figures below indicate section number along the channel)					
		1	2	3	4	5	6
22	PT3.0-DO	0.0389	0.0381	0.0366	0.0349	0.0331	0.0331
23	PT3.0-DO	0.0389	0.0386	0.0361	0.0346	0.0334	0.0334
24	NA	0.0437	0.0432	0.0424	0.0409	0.0402	0.0404

