Measuring Experiences with a Wet Steam Turbine

R.G. Schmidt
Universität der Bundeswehr Hamburg, Germany

1. Introduction

The Expansion in a multistage wet steam turbine is characterized by subcooling, spontaneous condensation and two–phase interaction. After the first spontaneous condensation the greatest fraction of wetness consists of fog droplets. The size of the fog droplets is responsible for the amount of the wetness loss, the fraction of coarse water and the intensity of the erosion. A detailed understanding of these processes would have a decisive influence on the development of calculation procedures to predict the real steam state in the wet steam stages over the whole load region. In addition a reliable knowledge about these processes would enable a turbine designer to minimize the wetness loss in wet steam turbines of every type and size.

The state variables of steam during such a real expansion differ from those, which are found in an expansion of full thermodynamic equilibrium, and are characteristic for the actual subcooling, the position of the condensation shock and the size of the fog droplets. Therefore it is possible to compare experimental results received by means of a highly precise measurement equipment with the results of corresponding throughflow models of the turbine. This procedure would supply a clear information about the real expansion process [1]. The development and testing of such a measurement equipment is subject of this paper.

2. Experimental turbine

For the experiments a 6–stage condensing steam turbine as being in use for driving turbo–generators was coupled via a reducing gear to an eddy current brake and connected to the steam circuit of the laboratory. The turbine is designed as an impulse turbine in wheel–chamber construction with the last stage having 24 % degree of reaction in the mean section (s. Fig. 1). The impulse wheels of the stages 1—5 are equiped with shrouds and have an axial gland collar between the guide vanes and the rotor blades. The blade tips of the reaction wheel of the 6. stage are tapered for sealing.

The live steam is fed into the valve chest through two manually adjusted control valves on both sides of the cylinder. From there the steam directly flows into the wheel chamber, as the Curtis stage was removed to adapt the turbine to the live steam state of the laboratory.

3. Measurement equipment

3.1 General

As the differences of the steam behaviour can only be recognized by small differences in the steam state variables, a high precision of the measurement equipment is necessary. The velocity of the data logging is of less importance, because the measurements will take place in the steady state condition as it is usual for steam turbines. However the natural oscillation of the steam circuit, which effects a periodic change (T $\approx$ 8 min) of live steam pressure and temperature with a small amplitude, demands a lower bound for the data logging velocity to measure all values exactly in the same load condition.

Fig. 2 shows the positions and the numbers of the measuring points logging the following variables:

1, 2: atmospheric pressure as reference
3, 4: plate orifice according to DIN 1952, differential pressure and static pressure behind the plate orifice
6, 7: wheel chamber total pressure
9–26: pressure of each stage (3 per stage)
27, 28: torque and speed of the eddy current brake
29: temperature in front of the plate orifice
30: wheel chamber total temperature
31–36: recovery temperature in front of each guide vane ring (1 per stage)
37, 38: exhaust steam total temperature
39: steam temperature behind the exhaust flange

The positions 1 and 2 are the measuring points in the radial holes of the upper half casing. The measuring points in the cylinder joint are position 3.

3.2 Pressure Measurement

The most effort was invested in the pressure measuring, as in the wet steam region a reliable information about the expansion can only be expected from the pressures. The wetness fraction, the subcooling and the flow conditions at the temperature measuring points are unknown.

The pressure in each wheel chamber can be measured radially above the shroud because of the turbine's impulse type construction. Considering a radial pressure gradient the measured pressure is converted to the mean section and thus can be compared with the calculated pressure for this point. Therefore in the cylinder joint of the upper half casing a pressure measuring tube was installed for each stage (s. Fig. 3a). These tubes with an inner diameter of 5 mm penetrate the cylinder wall just above the shrouds. In addition radial holes were drilled into both sides of each wheel chamber of the upper half casing. Tubes with an inner diameter of 6 mm were fitted in these holes (s. Fig. 3b). All tubes are flush mounted with the inner cylinder wall. Because of the little flow velocity above the shrouds no significant measuring faults have to be expected in spite of the relatively thick tubes [2]. The upper half casing was choosen for these installations, because it is easy to handle and accessible from all sides. Beginning from the measuring point the pressure tubes were installed with increasing height, so that condensing steam can flow back into the turbine without causing measuring errors by accumulating to a water column (s. Fig. 4). These 8 x 6 mm steel tubes are then fitted to directional control valves with 3 connections and 2 switching positions, which are mounted on both sides in a certain lateral distance above the measuring points on a common mounting for each side. Activating these valves the pressure tubes between valve and measuring point are purged by pressurized air [3]. Afterwards the pressure signals reach the pressure transducers over 8 x 6 mm transparent, flexible tubes. These tubes are filled with water and are placed with decreasing height to the transducers. A stop valve is installed directly behind the purging valve to shut off the tube to the measuring point. By closing the stop valve it is possible to aerate the flexible tube with atmospheric pressure and to refil the water column in the flexible tube while the turbine being in operation. This action is also necessary for a zero pressure compensation by measuring the pressure of the water column. During the tests the water–level always has to be at the top of the flexible tube to avoid measuring errors.

Both pressure measuring points at the plate orifice are equiped with compensating vessels. During operation the water–level reaches the lower rim of the measuring tube to the plate orifice, but this cannot easily be checked from outside. Therefore steel tubes are fitted at the top of these vessels and are installed with increasing height via security stop valves to another stop valve each, which are used for aeration with atmospheric pressure. Behind these valves the water filled flexible tubes are placed with decreasing height to a differential pressure transducer. The pressure signal measured behind the plate orifice is connected with a reference pressure transducer via a third stop valve and flexible tube to determine the live steam pressure.

All measuring points with pressures higher or a little lower than atmospheric pressure are equiped with reference pressure transducers of the type PDCR 820 from Druck Ltd. At measuring points with clearly negative pressures absolute pressure transducers of the type PDCR 920 are used; the zero pressure of such a transducer has to be determined by measuring the height of the water column and its density. The atmospheric pressure is directly measured by absolute pressure transducers of the type PDCR 920 in the heating chamber. The differential pressure transducer is of the PDCR 120 type. All transducers, which are connected with a flexible tube, have a front diaphragm to avoid hollow spaces, from where the air cannot be removed when filling up the flexible tubes. Negative pressure tubes have to be connected very carefully, because the admission of smallest amounts of air would result in large bubbles, which displace the water column and cause measuring faults. All transducers are kept in the heating chamber at a constant temperature of 40° C. They are designed for a supply with pulsed constant current of 13.2 mA and under these conditions they reach an accuracy of 0.06 % f. s. (non—linearity, hysteresis and consistency). The constant current supply avoids measuring errors by varying resistance in the connections. The pulse duration of about 25 ms prevents a heating up of the transducer as it would happen using a continous current supply. All transducers were calibrated under laboratory conditions to make good use of this offered accuracy. As the water—levels can vary about ± 5 mm, the accuracy is limited to ± 0.5 mbar.

3.3 Temperature Measurement

All temperatures are measured by means of Thermocoax miniature wrapped thermocouples from Philips. They are of the NiCr—Ni type wrapped by Inconel. Their accuracy amounts to the higher value of ± 0.5° C or $\pm\ 0.0013 \cdot |\vartheta|$ with ϑ as Celsius temperature. This is according to 1/3 DIN IEC 584 cl. 1. Their soldered point is inside the wrapping to achieve a greater temperature inertia during measuring, when water droplets are hitting the thermocouple. The thermocouples were soldered onto the leading edges of the guide vanes near the cylinder joint by a high temperature soft solder (s. Fig. 5). The thermocouples were laid through channels in the cylinder joint and through the exhaust section out of the turbine. These measuring points deliver the recovery temperature in front of each guide vane ring.

The wheel chamber total temperature is measured by means of a total temperature probe in the valve chest. The exhaust steam temperature is measured by two total temperature probes in the mean section about four pitches behind the last rotor wheel. All three probes are of the same type. Their wrapping tubes are open at the end, so that condensing steam can drop down (s. Fig. 6).

Dead end tubes with thermocouples were installed in front of the plate orifice to measure the live steam temperature and behind the exhaust flange to measure the exhaust steam temperature behind the turbine.

All thermocouples are connected to compensating soldered points, which are in a common oil tank, which is automatically kept at 0 ± 0.1° C by a Peltier cell.

3.4 Torque and Speed Measurement

The torque and the speed are measured at the eddy current brake. It is carried in pendulum bearings and is supported by a torque balance. A bridge circuit with a slipring resistor delivers a voltage signal depending on load. The torque balance was calibrated to receive the relation between output voltage and torque. The accuracy amounts to 0.25 % and is characterized by a significant hysteresis, which is caused by the friction in the load transmission from the brake to the torque balance and the potentiometer pickoff. The speed is measured inductively at a toothed wheel with 60 teeth on the brake shaft delivering a frequency signal. The accuracy of the speed measurement amounts to ± 0.5 1/min; this is ± 0.03 % at the low speed gear shaft for a nominal speed of 1800 1/min.

3.5 Measuring Procedure

The logging and processing of all measured data is performed by a COMPULOG THREE computer from Digital Equipment Corporation. While the voltage signal of the thermocouples is immediately switched to the amplifier, the output voltage of the pressure transducer and torque balance channels is at first measured without power supply and afterwards with activated power supply. The result is the difference between both measurements. In this way parasitic voltages are compensated. The speed signal is logged by a frequency channel. A status channel activates the purging valves. After reaching steady state condition the whole measuring procedure is started and controlled by a computer program [4].

4. Results

The following measuring procedure proved to be most efficient. The purging facility was activated for 0.5 s. This duration was enough because of the short length (1.0 — 2.0 m) of the measuring tubes. After a damping period of 5 min the first measurement is started. One single measurement takes about 6 — 9 s. The further single measurements follow at intervals of 2 minutes.

The arithmetic average values are calculated from the single measurements for one load condition. A more frequent purging, e. g. before each single measurement, would cause large amounts of air accumulating in the condenser and increasing the saturation vapour pressure. A too long and too frequent purging even effected water shocks in the condenser and forced to reduce the power of the steam circuit. As even smaller amounts of air disturb the condenser, it is necessary to allow the indicated damping period.

The processing of the measured values showed the pressure measurement to be very reliable and accurate confirming the expectations. As the pressures of the relative pressure transducers and of the atmospheric pressure transducers are added, also the measuring faults are added. The differential pressure measurement shows the least accuracy, because here the uncertainties of the water—levels are adding up and the differential pressures have relatively small values.

The measured temperatures can only be evaluated in the superheated steam region, as water droplets impinging on the thermocouples and evapourating there would have a cooling effect and cause measuring faults. The low flow velocity in the boundary layer of such a thermocouple would make the steam return to thermodynamic equilibrium. A subcooling cannot be detected by such an equipment.

The mass flow is calculated from the measured values according to DIN 1952 by using the IFC state equations [5] taking into account the behaviour of real gas.

In Fig. 7 the relative measuring faults and the standard deviations of a representative series of 6 single measurements are presented for the parameters turbine total mass flow, total pressure and total temperature in the wheel chamber, pressure and temperature behind the 4. stage and power at the coupling. The comparison of the single measurements shows, that the amount and the sign of the relative measuring faults are continuously changing during one series of measurements. As this behaviour is characteristic for all series of measurements though the steady state condition has been reached a long time before, it can only be caused by the natural oscillation of the steam circuit having a time constant of this order of magnitude. Since the natural oscillations induce a periodic increase and decrease of the pressure and temperature at the boiler exit, the standard deviation is primarily characterized by the amplitude of the natural oscillation as a systematic measuring fault and less by a stochastic fluctuation. This underlines the high accuracy of the measurements. However the accuracy depends on the temporal position and duration of a series of measurements relatively to such an oscillation period. It does not seem necessary to separate systematic and stochastic measuring faults.

The individual measured values have quite different standard deviations. The mass flow reaches the highest values because of the above mentioned characteristics of the differential pressure measurement and the combination of several measured values. The standard deviations of the pressures are greater than those of the temperatures. This is caused by the characteristic of the boiler. The hysteresis of the torque measurement is responsible for the higher standard deviation of the turbine power at the coupling.

Conclusively the received series of measurements are a very suitable experimental base for theoretical investigations.

5. Bibliography

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[3] Moore, M. J.: Instrumentation for wet steam (in: Two—phase steam flow in turbines and separators). Washington: Hemisphere Publishing Corporation 1976.

[4] Reßing, C.: Meßwerterfassung für eine Dampfturbine. Diplomarbeit Universität der Bundeswehr Hamburg 1990.

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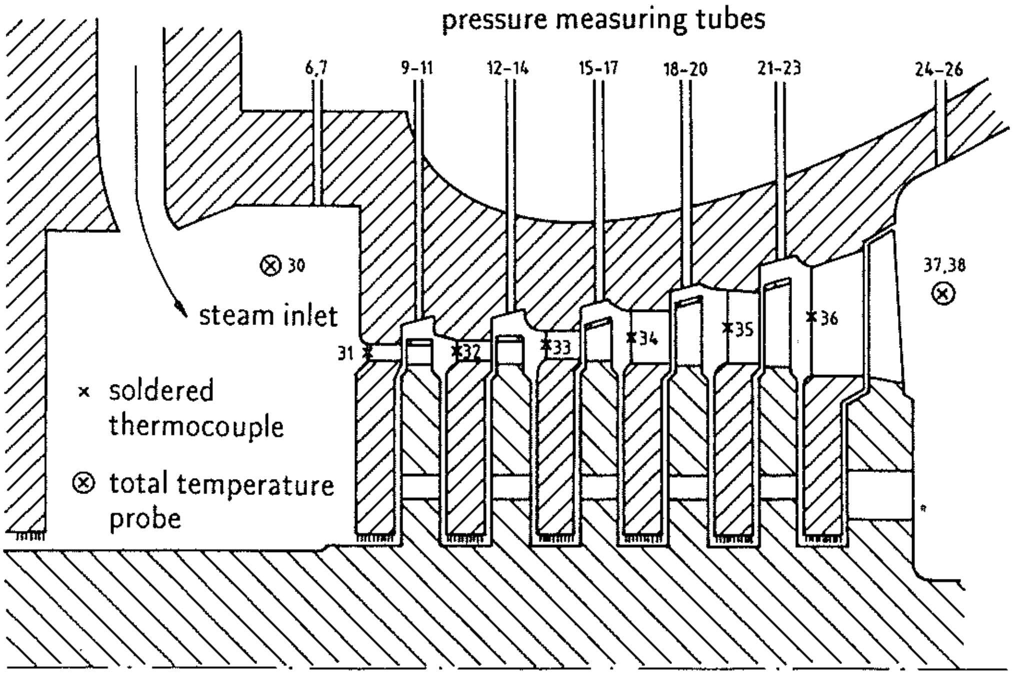
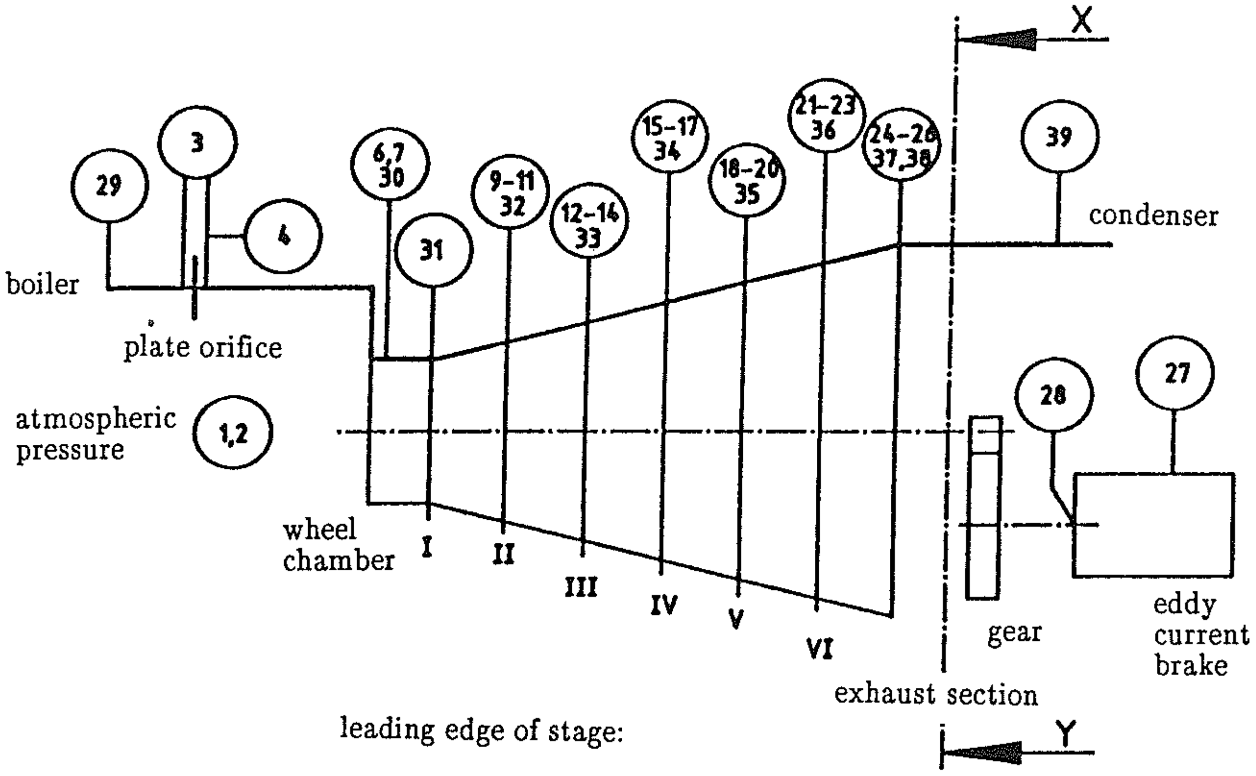


Fig. 1: Cross section of the experimental turbine



Section X - Y

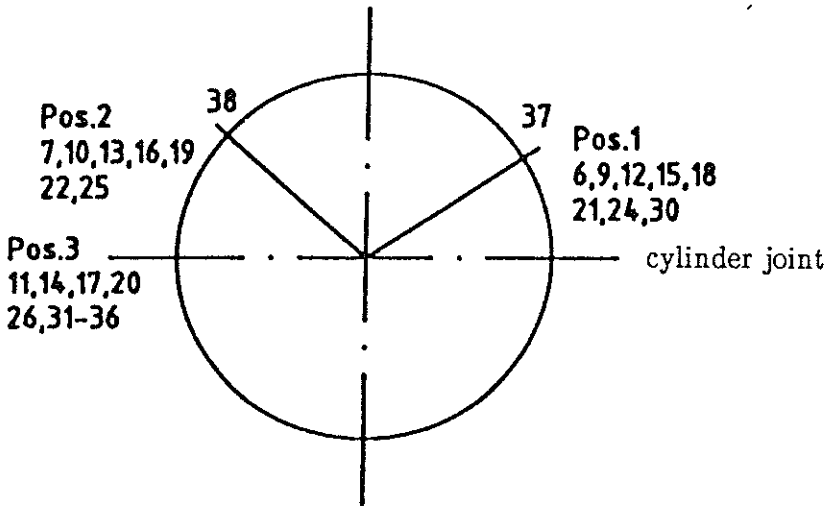


Fig. 2: Positions of the measuring points

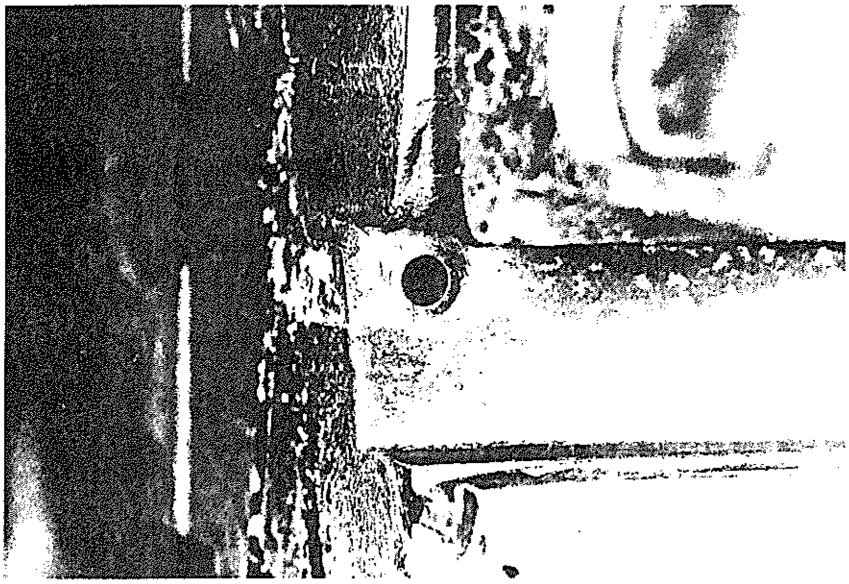


Fig. 3a: Pressure measuring points (cylinder joint)

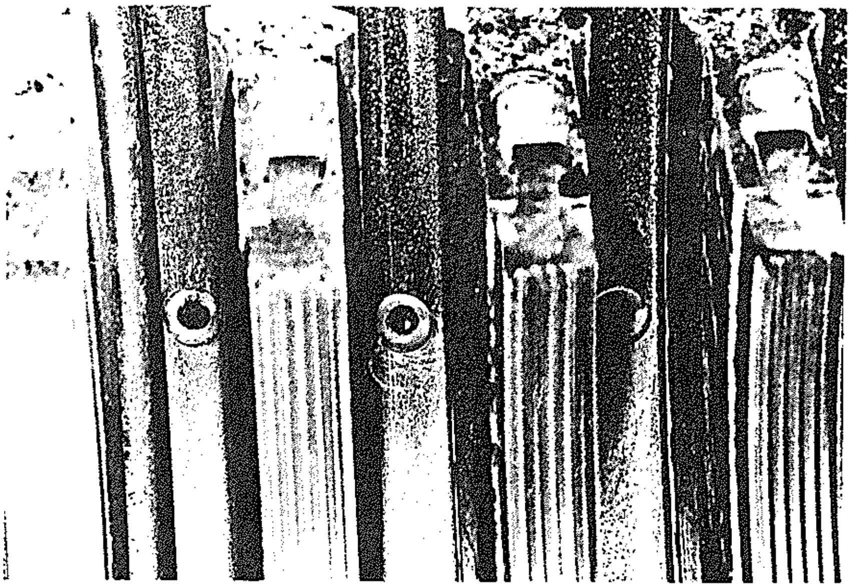


Fig. 3b: Pressure measuring points (radial holes)

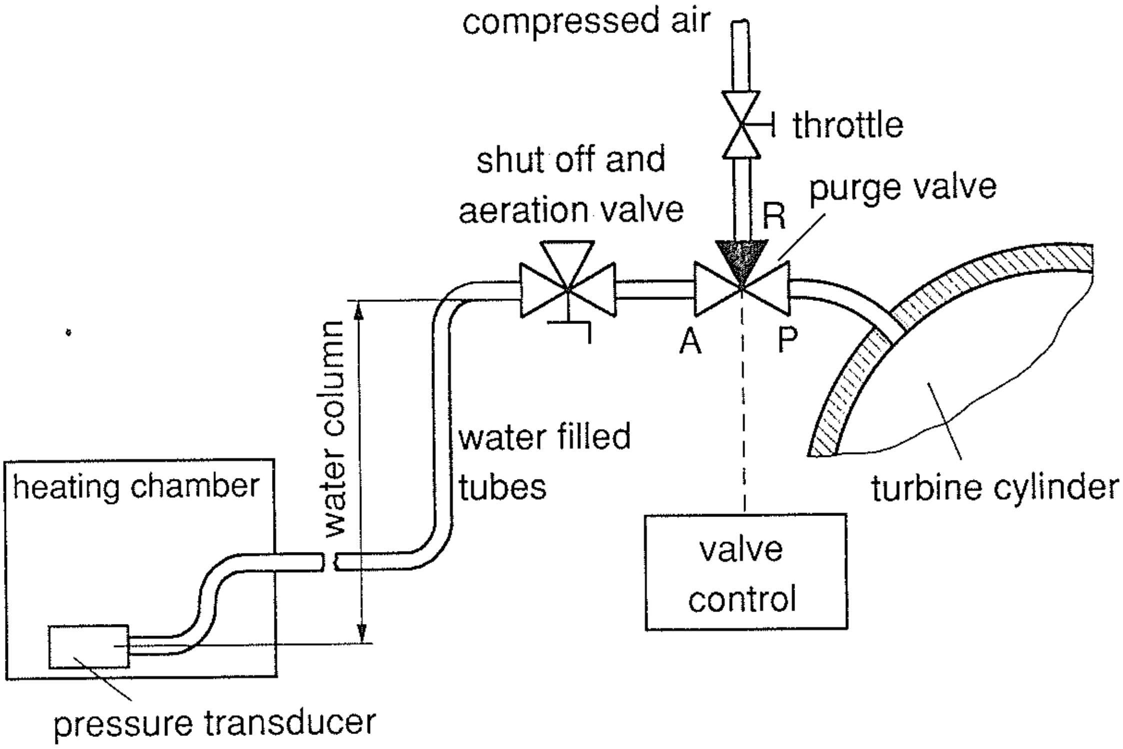


Fig. 4: Pressure measuring instrumentation

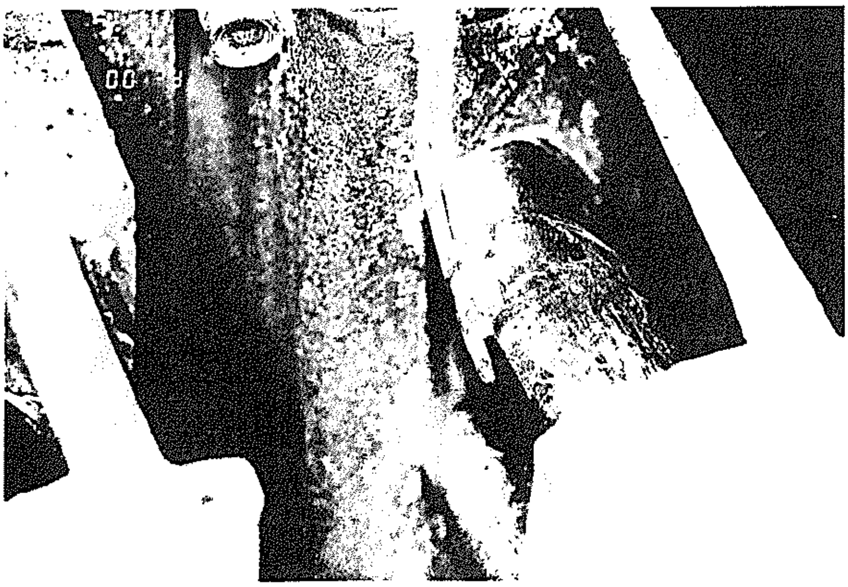


Fig. 5: Thermocouple soldered on the leading edge of a guide vane

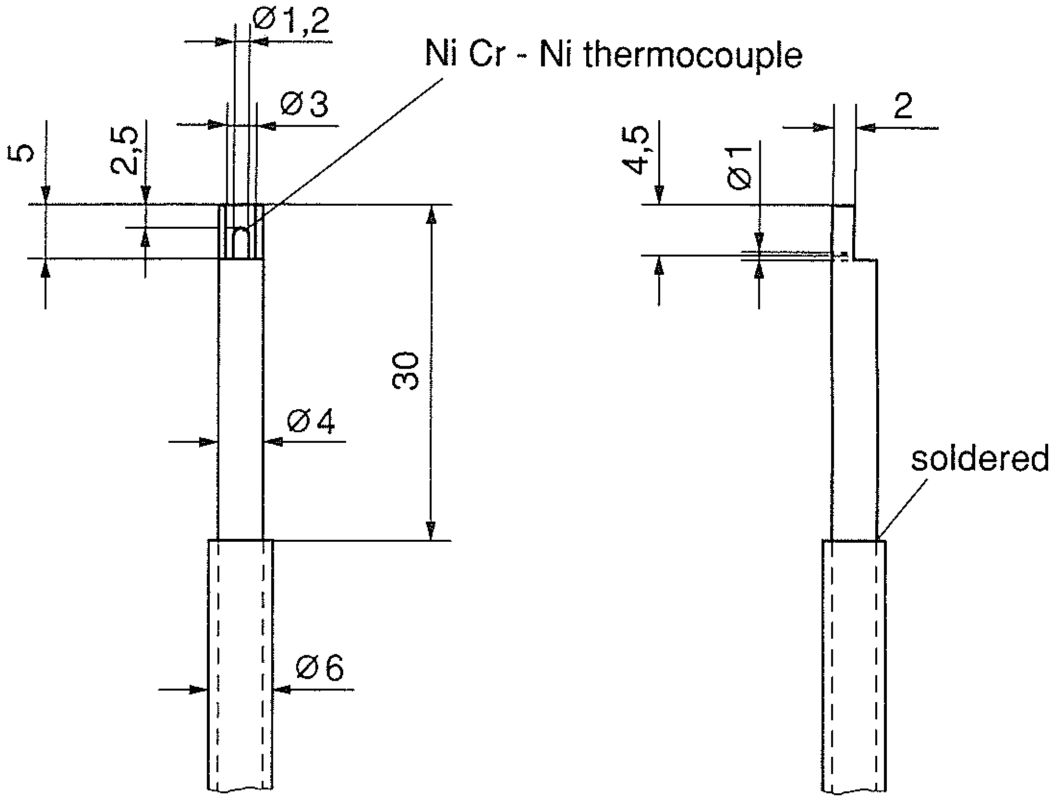


Fig. 6: Total temperature probe for wet steam

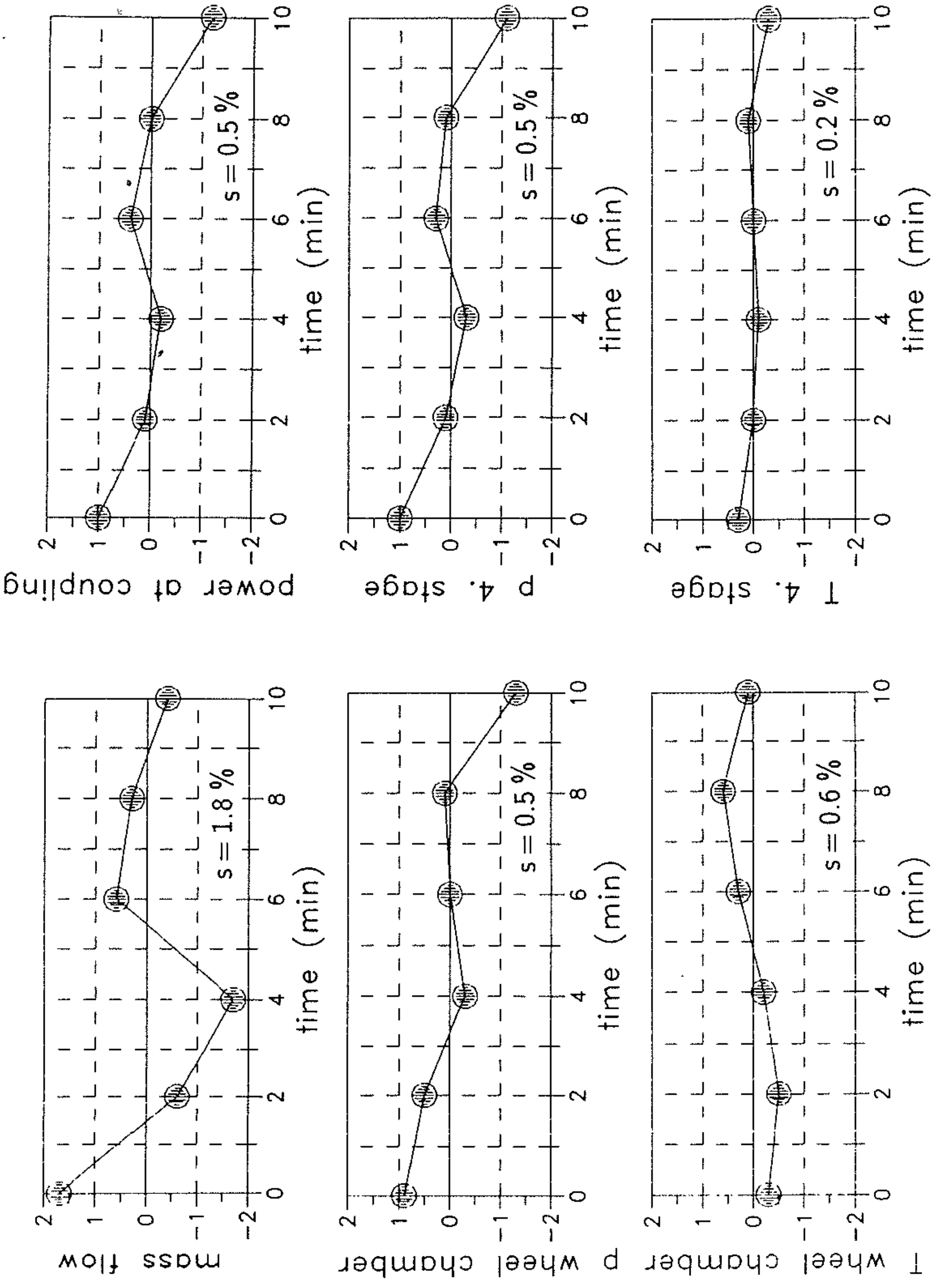


Fig. 7: Relative measuring errors and standard deviations of a typical series of measurements in %