204 THERMOHYDRAULIC VERIFICATION DURING THTR STEAM GENERATOR COMMISSIONING

C. HENRY
Sulzer Brothers Ltd,
Winterthur, Switzerland

C. ELTER
Hochtemperatur-Reaktorbau GmbH,
Mannheim, Federal Republic of Germany

Abstract

In one of the six THTR 300 steam generators thermocouples are installed inside the heat transfer tube bundles for measuring the gas and steam temperatures. Fluid temperature distribution measurements along and across the helix bundle have been recorded in its first months of operation over a load range of 40 % up to 100 % for steady state and transient conditions. Using these measurements as well as the rest of the operating instrumentation, the computer programs for the design of heat exchanger heat transfer areas are verified. The temperature measurements for steady state conditions are compared with predictions obtained in the design stage.

In these codes, the heat transferred from the outside helium gas to the water/steam inside the tubes is determined in discrete steps along the heating surface by one- and twophase heat transfer correlations. The degree of conformity between prediction and measurement is discussed and compared with more recent correlations.

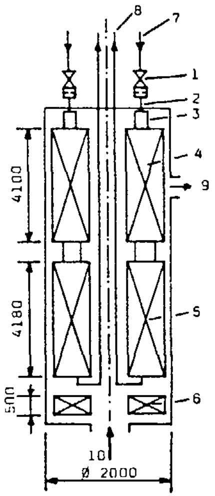
---

1. Introduction

At the THTR 300 MW prototype nuclear power station six steam generators of the helical type are installed. In order to achieve a most economic flow of the heating helium gas, the principle of downward flow evaporation has been adopted. On Sept. 23, 1986 the power plant reached full power. During the commissioning period before that day and also afterwards, gas and water/steam temperatures along and across the bundle have been recorded and will be presented in this article. They will also be compared with the prediction made by a linear computer code.

2. Basic Bundle Geometry

The principle bundle geometry is shown on Fig. 1. The helical bundle consists of 80 parallel tubes arranged in 15 cylinders 38.33 mm apart comprising 4 to 7 tubes per cylinder. The feedwater flow in 40 system tubes is divided into the 80 bundle tubes by wyes above the bundle. Each of the 40 system tubes is equiped with a throttle valve and an orifice. This combination is required to establish satisfactory flow stability, while the throttle valves supply a mean of adjusting the feedwater flow distribution in order to achieve a uniform temperature profile across the bundle.



1	40 throttle valves with orifice	6	reheater bundle
2	40 system tubes	7	feedwater line
3	80 parallel tubes	8	steam line
4	upper HP bundle	9	cold gas outlet
5	lower HP bundle	10	hot gas inlet

Fig. 1: Principle bundle geometry

3. High Pressure Bundle Instrumentation

In steam generator Nr. 3 a number of thermocouples are installed along the lower HP bundle tubes. They are arranged in section I to IX (see Fig. 2).

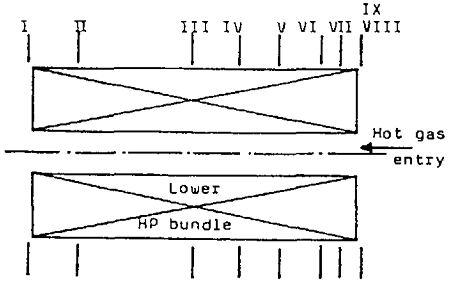


Fig. 2: Lower HP bundle with instrumentation sections I to IX

Table 1 indicates the number of thermocouples per section and the fluid considered:

Table 1: Number of thermocouples installed in lower HP bundle

Section	I	II	III	IV	V	VI	VII	VIII	IX
Nr. of thermocouples	4	8	8	5	5	5	5	9	8
Fluid S = Steam G = Helium Gas	G	S	G	S	S	S	S	G	S

Section V is positioned at the bimetallic weld joint. Tube material between sections V and VIII is Incoloy 800 and between sections I and V 15 Mo 3 and 10 CrMo 9 10.

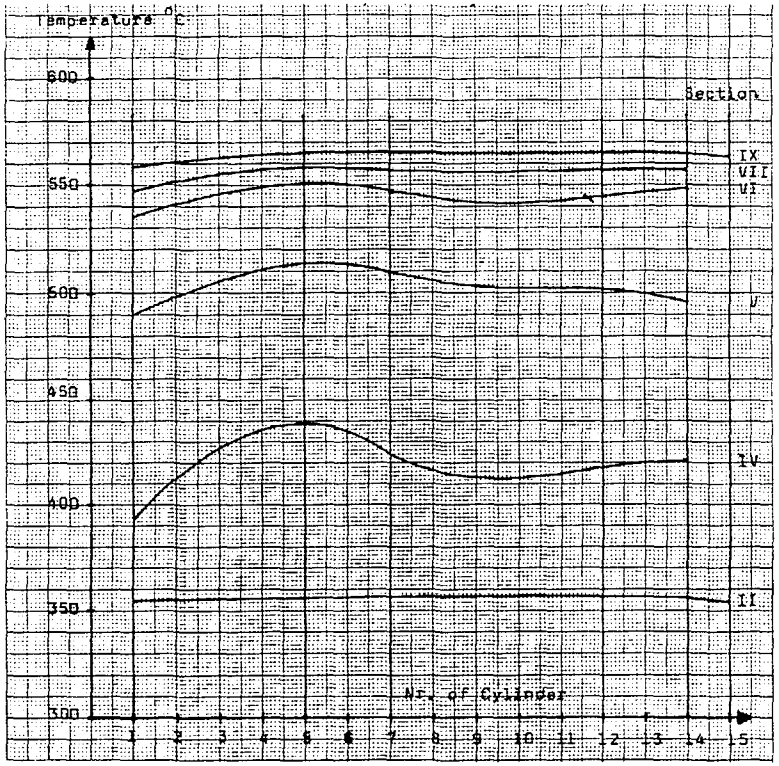


Fig. 3: THTR 300 MW steam generator radial temperature distribution in various sections, 40% load, steam temperatures

4. Temperature Distribution across the Bundle

Fig. 3 shows the radial temperature distribution for the 40 % load case, Fig. 4 for the 100 % load case. It should be noted, that the thermocouples in one section are not only arranged on different cylinders, but also spread over the circumference. For the plots in Fig. 3 and Fig. 4 the assumption was made, that the temperature measured in a cylinder remains constant along the circumference of this cylinder. Therefore, the temperature profiles represent average values with respect to the circumference.

Several specific features can be observed:

- In section IX (steam temperature at bundle exit) a fairly uniform radial distribution can be found. The deviations from the mean value are -5 °C/+2 °C for the 40 % load case and -6 °C/+2 °C for the 100 % load case. The extreme mini-

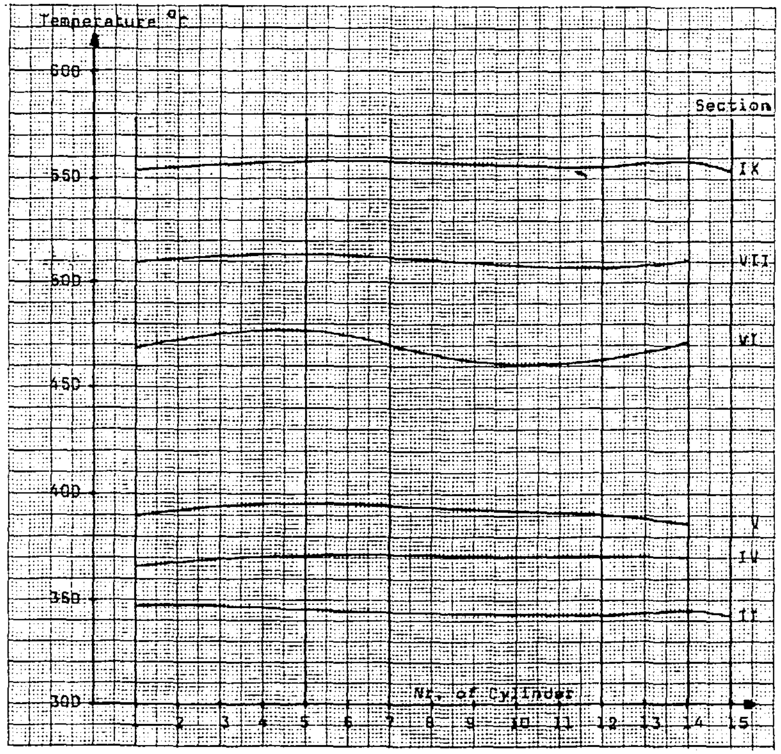


Fig. 4: THTR 300 MW steam generator radial temperature distribution in various sections, 100% load, steam temperatures

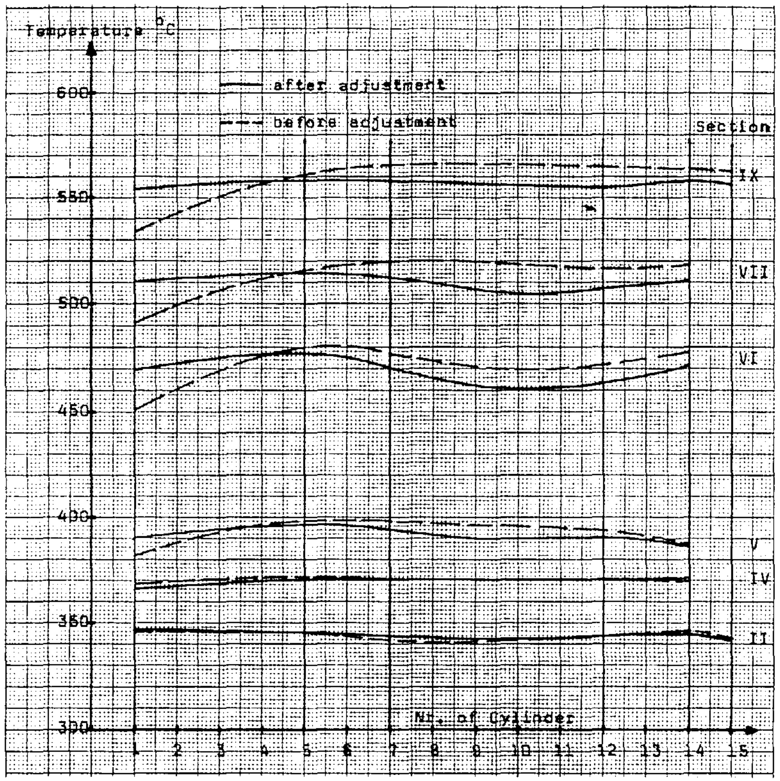


Fig. 5: THTR 300 MW steam generator radial temperature distribution in various sections, effect of adjustment of throttle valves

mum lies at the innermost cylinder. A limited possibility to correct this temperature would exist by an adjustment of the throttle valves. However, if the steam temperature before the turbine inlet reaches the required value, no upwards correction of this temperature is required and advised, since the lower temperature is more favourable with respect to the stresses in the tube wall. The efficiency of an adjustment of the throttle valves is demonstrated in Fig. 5 and described in para. 5.

- In section V (bimetallic weld) the allowable steam temperature is limited in two ways:

a) The design temperature of the tube wall being 485 °C (100 %) and 526 °C (40 %) must not be exceeded. This corresponds to a maximum permissible steam temperature of 441 °C (100 %) and 509 °C (40 %). The measured values amount to 391 °C and 502 °C respectively.

b) A certain superheat must be maintained to prevent fatigue damage of the bimetallic weld due to eventual heat transfer fluctuations. The measurements show a superheat of 21 °C (100 %) and 83 °C (40 %), see also Fig. 6 and 7. Such heat transfer fluctuations are unavoidable, when the tube wall is exposed to alternating contact with superheated steam (one phase, low heat transfer) and steam/water mixture (two phase, film boiling with high heat transfer).

A further reason to maintain superheat in the austenitic section is that corrosion due to deposition products can not occur, as such depositions take place in the last evaporator section, which is before the bimetallic weld.

5. Adjustment of Throttle Valves

Prior to commissioning of the steam generators all 40 throttle valves were set to their theoretically predetermined opening values. During commissioning certain throttle valves were readjusted with the aim of achieving a more uniform radial steam temperature profile at the bundle exit. Fig. 5 shows the temperature profiles before and after the adjustments. The steam generator thermal output for both measurements were similar within a few percent (100 % load).

The shape of the profile before the adjustment indicates the necessity of throttling the feedwater flow through the inner cylinders further than predicted. In Table 2 the adjustments made to the various throttling valves are listed relative to the maximum. A positive sign represents closing of the valve, a negative sign opening of the valve.

Table 2: Relative adjustments of throttle valves:
+: close valve
-: open valve

Cylinder Nr.	Adjustment $\Delta h / \Delta h_o$
1	+1.00
2	+0.46
3	+0.31
4	+0.27
5	+0.31
14	-0.15

Δh = valve stroke adjustment

Δh_o = average valve stroke adjustment of cylinder No. 1 (Δh_o = 1.3 mm)

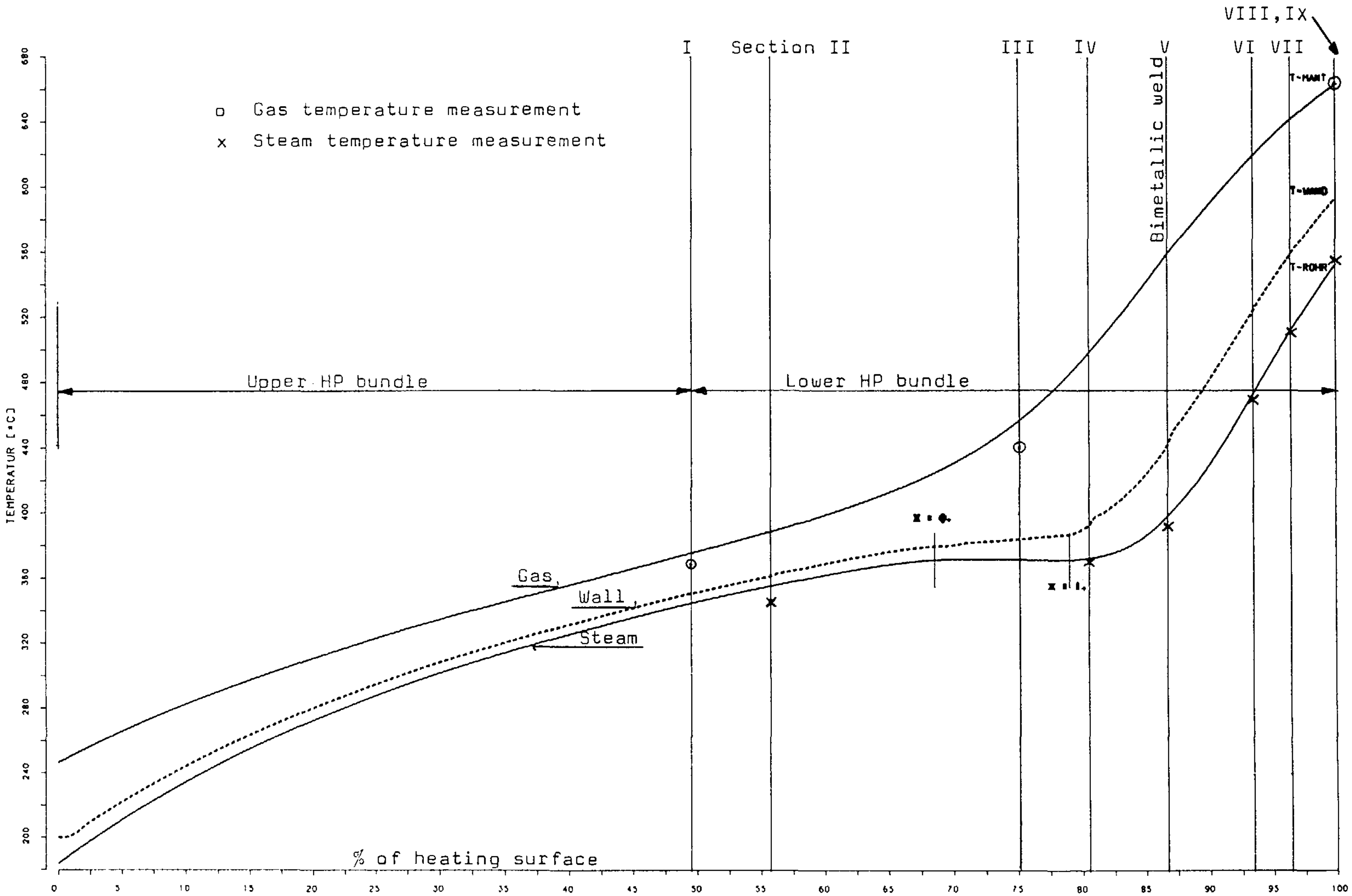


Fig. 6: THTR Steam Generator 100% Load: Temperature distribution

Output: 107.116 MW

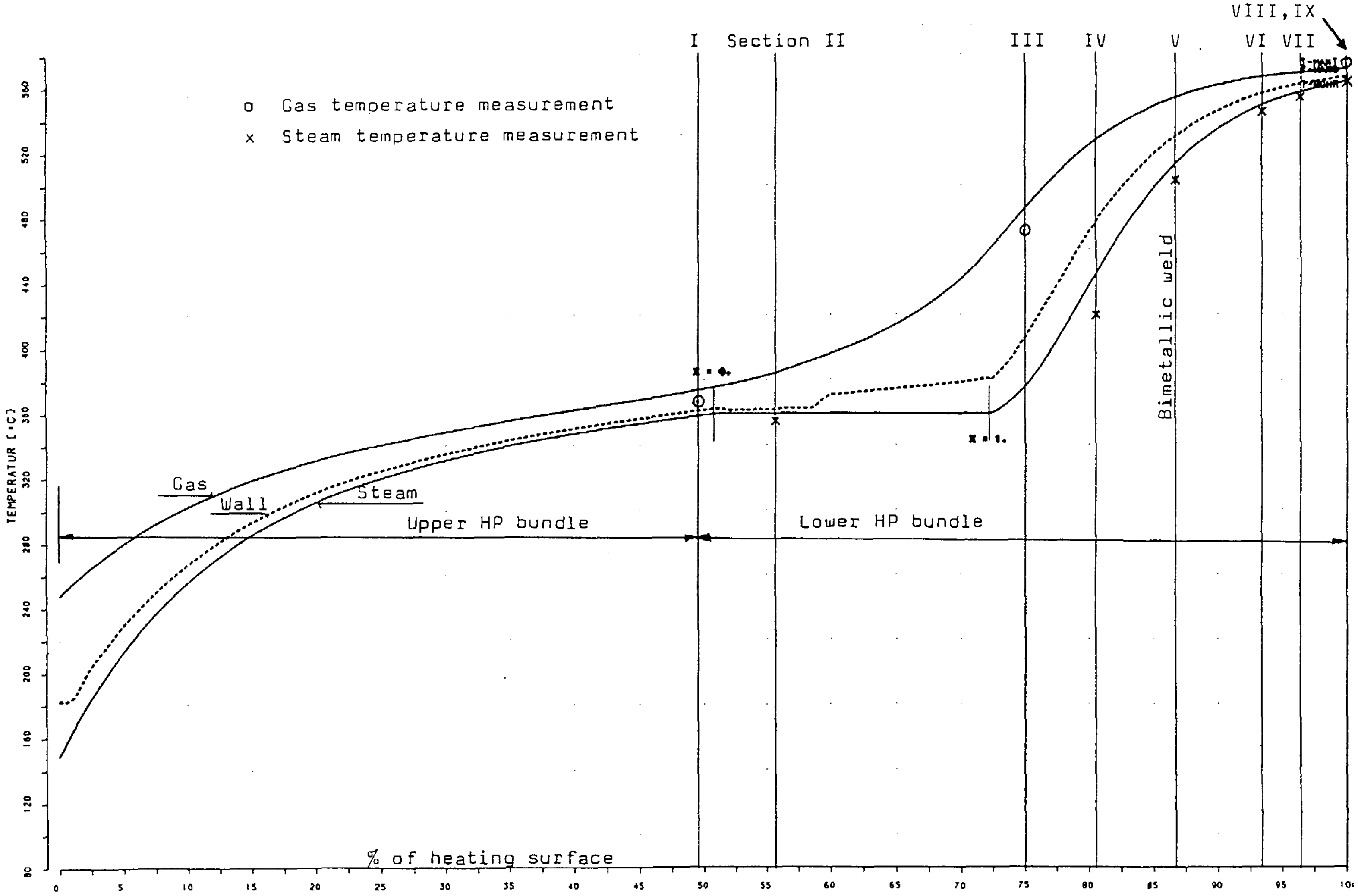


Fig. 7: THTR Steam Generator 40% Load: Temperature distribution
Output: 46.264 MW

6. Temperature Distribution along the Bundle

Temperatures measured in one section were averaged and the mean values plotted against the tube heating surface (see Fig. 6 for 100 % load and Fig. 7 for 40 % load). To compare the measured temperatures with the predicted ones, a thermohydraulic calculation was made using the same boundary conditions as for the measurements. These boundary conditions include gas mass flow, feedwater massflow, cold gas outlet temperature, feedwater inlet temperature and pressure. As cold gas outlet and feedwater inlet temperature are not measured exactly at the cold end of the heating surface, an estimate of the temperature difference between the measuring position and the bundle start had to be made: feedwater heated up by 3 °C for 40 % load, 2 °C for 100 % load, cold gas cooled down by 3 °C for 40 % load, 2 °C for 100 % load. Table 3 comprises the boundary conditions assumed for the 40 % and 100 % load calculation:

Table 3: Boundary conditions for verification calculation
(* = calculation output)

Load	Gas				Water/Steam				
		Inlet *)		Outlet		Inlet		Outlet *)	
	$\dot{m}$	T	p	T	$\dot{m}$	p	T	p	T
40 %	27.53	571.2	38.5	247.7	16.43	185.4	148.8	181.9	563.5
100 %	49.36	664.2	38.5	246.6	40.99	218.2	183.9	203.3	554.2
	kg/s	°C	bar						

Generally, predictions and measurements coincide well, the measured temperatures being slightly below the prediction. However, very good conformity is achieved at gas inlet and steam outlet, which is partly subject to the influence of the above mentioned assumptions about the cold end temperatures. These facts lead to the conclusion, that heat transfer coefficients in the evaporator and superheater section are slightly underpredicted. For the economizer section no comparison between prediction and reality can be made due to lack of measurements along this part.

A further verification calculation for the 100 % load case was performed using the HRB code DERZ. Assuming the same corrections of the temperatures at the cold end, the calculated heating surface is 3.3 % smaller than installed.

Fig. 8 shows the temperature profile along the calculated heating surface and the actual temperature measurements. It can be concluded, that the heat transfer coefficients in superheater 1 are slightly underpredicted. This same result has been found by using the afore mentioned code.

A further result of the calculation is the gas side pressure drop. For a helium mass flow of 48.13 kg/sec a Δ p of 0.3225 bar was measured. For the nominal mass flow of 49.25 kg/sec the corrected Δ p amounts to 0.3377 bar. This value coincides well with the prediction of Δ p = 0.371 bar.

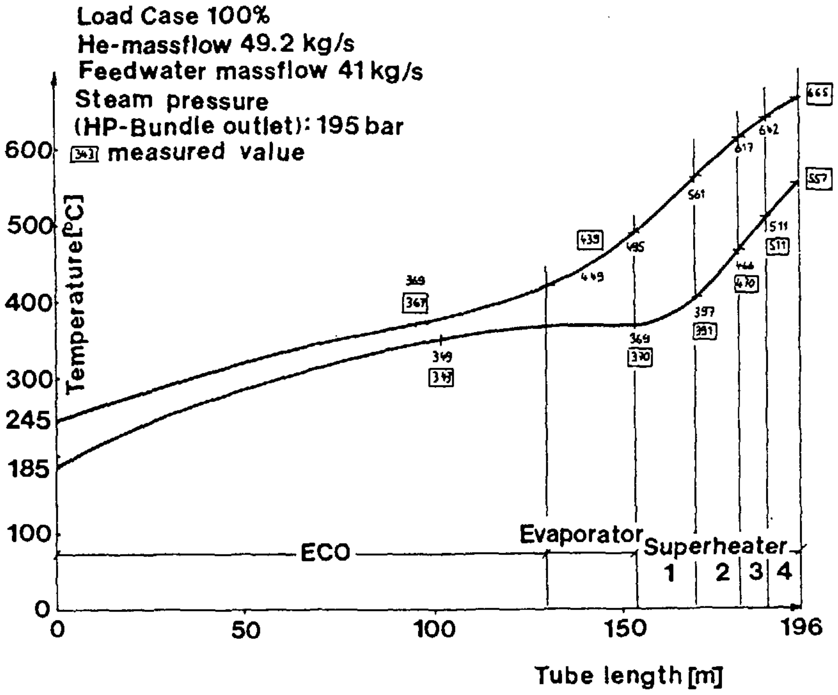


Fig. 8: Temperature distribution along the HP-bundle

7. Thermohydraulic Calculation Code DISTEMP

The computer code DISTEMP was designed to perform thermohydraulic calculations of gas heated spiral type steam generators. In its present form it is not suitable for sizing calculations, but only for simulation calculation, i.e. the steam generator thermal performance is worked out based on a given tube bundle. The output mainly consists of gas-, water/steam- and tube wall temperatures along the bundle representing mean values across the bundle.

DISTEMP is a linear code, that determines the heat flow from the gas to the water or steam using conventional heat transfer correlations. The calculations are started at the "cold end" of the steam generator and repeated stepwise along the heating surface using the results of the previous step as input for the actual step, until the end of the surface is reached.

Some special features implemented in DISTEMP are to be mentioned:

- Option to include a hot spot factor, taking into consideration the nonuniform gas side heat transfer coefficient along the tube circumference.
- Option to upgrade or downgrade the theoretical heat transfer and pressure drop coefficients.
- Option to enter different fouling resistances in economizer, evaporator and superheater section.
- Temperature plot subroutine available.

8. Thermohydraulic Calculation Code DERZ

The thermohydraulic calculation code DERZ is used by HRB for determining the heating surface area of a helically wound steam generator. Hereby, gas side heat transfer is calculated according to the slightly modified Grimison correlation including a flow factor, whereas waterside the Gnielinski correlation as described in the "VDI-Wärmeatlas 1974" is used.

The input consists of geometry, material properties, gas inlet and outlet temperature, pressure and mass flow rate. On the water side, also inlet and outlet temperatures and steam pressure must be specified.

The program calculates the required heating surface, pressure drops and additional geometrical data as e.g. number of tubes in the individual cylinders.

EXPERIMENTAL INVESTIGATIONS OF HEAT EXCHANGE AND HYDRODYNAMICS ON MODELS OF A VG-400 STEAM GENERATOR TUBE BUNDLE MADE UP OF SMALL DIAMETER HELICOILS

V.F. GOLOVKO, N.A. IVASKOV, P.I. OBUKHOV,
V.N. POSPELOV, A.I. SERGEEV
I.V. Kurchatov Institute of Atomic Energy,
Moscow, Union of Soviet Socialist Republics

Abstract

Features of HTGR steam generators having heat exchange surface made up of small diameter helicoils are discussed in the paper. A general approach to optimization of thermohydraulic characteristics of ВГ-400 steam generator design backed by calculation and experiment are given. Main results of steam generator assembly's model aerodynamic test are presented. Data of thermohydraulic tests of a single tube model in a helium heated test rig are discussed.

At present when designing HTGR steam generators (SG) the USSR considers the possibility of using tube bundles made up of small diameter helicoidal coils. Such coils have the ratio of the mean coil diameter D_{cp} to the tube outer diameter d_{H} from 3 to 14. The minimum value of the ratio is defined by manufacturing considerations while the maximum value is defined by the coils' diameter effects on its thermohydraulic characteristics and by the coil's overall dimensions. The lower value is also limited by the increasing tubes' ovality when winding and by changes in wall thickness at the outer and inner generatrices.

The application of such coils is due to the features combining advantages of straight tube bundles and coils, i.e.