THTR – STEAM GENERATOR FLOW STABILITY

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Abstract

After a short review of the phenomenon of static instability - also called excursive instability - an overview of those specific features of the THTR steam generator follows, which must be observed when taking actions to prevent flow instabilities. These features are in detail:

- restricted number of tube penetrations
- tube arrangement within the helical bundle
- downhill flow
- part load conditions
- temperature limits for the ferritic/austenitic material transition joint.

Then the required stabilizing pressure drops and the means provided to produce these pressure drops are discussed:

- orifice in the single tube
- fixed orifice in the system tube
- adjustable orifice in the system tube.

General

The pressure drop in a heated tube consists of 5 components. They vary considerably for variable steam content x as shown in Fig. 1.

If we have a system of several heated tubes between common headers (as in a steam generator) the pressure drop of all the tubes is the same e. g. Δp_1 in Fig. 2. We see from curve A that this pressure drop can be produced by 3 different mass flows: G_1, G_2 and G_3. The mass flow G_2 is not stable: A small increase of the mass flow results in a lower pressure loss which enhances the mass flow until it reaches the value G_3. A small decrease of the mass flow on the other hand leads to a mass flow G_1.

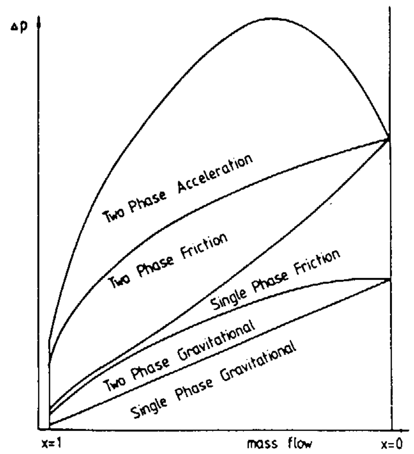


Fig. 1 Nature of 2 phase pressure drop

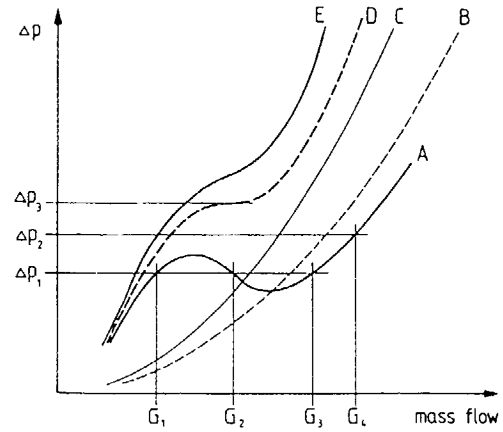


Fig. 2 Pressure drop characteristic

As the heat input to all the tubes is substantially the same, the temperature at the end of the heated tube section depends on the mass flow: G_1 is evaporated to a great deal or is possibly superheated whereas G_2 has not reached saturation temperature.

In a steam generator with identically heated tubes we cannot allow the tubes to carry different mass flows and produce different temperatures. Therefore we must change the pressure drop characteristic A by adding a pressure drop which does not depend on the heat input.

This is possible with an orifice in front of the heated section, the pressure loss of which is proportional to the square of the mass flow, as shown in curve C. The resultant pressure drop is shown in curve E. The magnitude of the added pressure drop has to be such that the slope of the resultant is always positiv. An orifice producing a pressure drop according to curve B would not yet be adequate because the resultant curve D has a region in which the mass flow producing a pressure drop Δp_3 is not well defined.

The ideal helix bundle

An ideal helical bundle has the following characteristics:

- constant transverse and longitudinal pitches s_T and s_L.

- the number of tubes N in the various cylinders is proportional to their diameters D:

$$\frac{N_i}{N_1} = \frac{D_i}{D_1} \qquad \text{with } N_i - N_{i-1} = 1,\ 2,\ 3 \quad \text{etc}$$

$$D_i - D_{i-1} = 2\ s_T$$

$$i = \text{number of cylinder}$$

Under these conditions all the tubes have the same length, are heated equally and carry about the same amount of water. The uniformity of distribution can only be slightly disturbed by the influence of the tube curvature. For the actual THTR helix diameters however this influence is less than 5 %.

The THTR-steam generator HP-bundle [1]

For the THTR-bundle dimensions the smallest ideal number of tubes would be 180 for the chosen tube diameter d_o = 25 mm. For various reasons this number cannot be realized:

- the total number of tubes has to be a multiple of the 40 positions available in the closures each for feedwater inlet and steam outlet

- for cost reasons the number must be kept as small as possible

- the pressure loss must be reasonable.

The choice was a total of 80 tubes being arranged in 15 cylinders as shown in Fig. 3.

This results in different tube lengths. They can be partially corrected by the use of 3 different longitudinal pitches. The remaining differences can be taken up by installing throttles which facilitate the adjustment of the flow in each tube according to its heat input. This is a condition in order to get:

- equal steam temperatures in all the tubes of every bundle section, especially at the end of the heating surface (including heated connecting tube sections).

- equal location of the end of evaporation at a satisfactory distance from the transition weld between ferritic and austenitic tubes.

The flow of the feedwater of 40 system tubes is divided into the 80 tubes of the bundle by bifurcations located above the bundle. Below the bundles pairs of tubes are again joined to arrive at 40 system tubes carrying the steam through the central duct of the steam generator to its top and through the penetration of the reactor pressure vessel (Fig. 4).

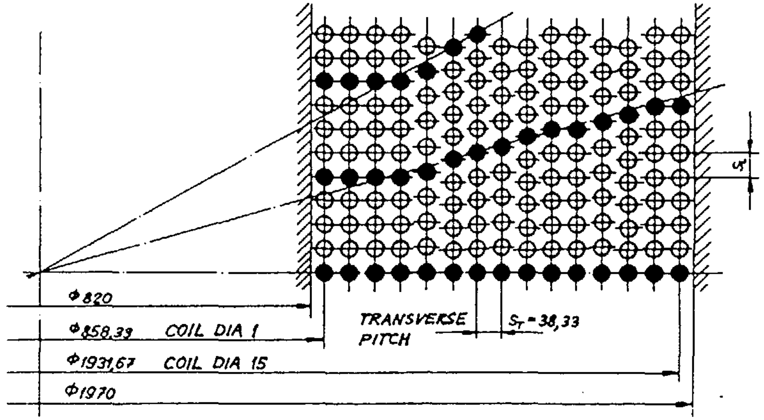
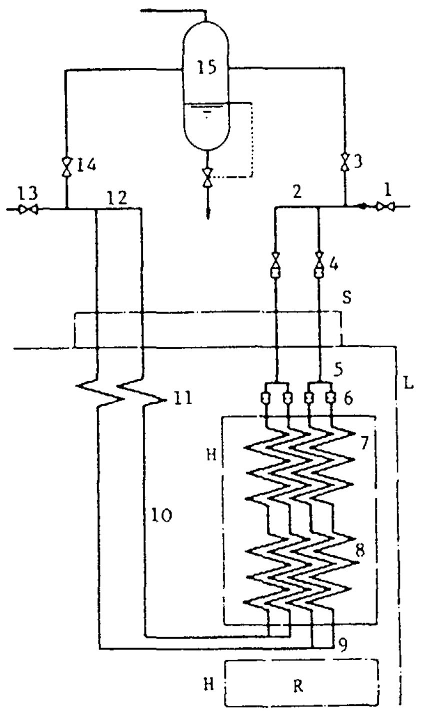


Fig. 3 Tube arrangement of the THTR high pressure bundle



1 Feedwater valve
2 Feedwater headers
3 Relief valve
4 40 Throttle valves
5 40 Bifurcations
6 80 Orifices
7 80 Upper helical coils
8 80 Lower helical coils
9 40 Tees
10 40 System lead outs
11 Expansion zone
12 HP steam header
13 Main steam valve
14 Start-up valve
15 Start-up vessel
H Heated zone
L Liner/primary closure
S Secondary closure
R Reheater

Fig. 4 Simplified flow sheet showing 1 of 6 steam generator units

Flow distribution considerations

Stability of the water distribution must exist for the 2 tubes within a system as well as for the systems among themselves. This requirement must be maintained at all loads between 40 and 100 % power at constant steam conditions as well as during the removal of residual heat with reduced steam pressure. It can be achieved with throttles, installed in each system tube and in each single tube before the entrance into the tube bundle.

All throttles in the single tubes have the same dimension and give a pressure drop of 5 bar for nominal flow. This is possible because the 2 tubes of 37 systems have the same length as they are located in the same cylinder. Only 6 tubes of those cylinders with uneven tube numbers have slightly different lengths within their 3 systems.

Fig. 5 shows a bifurcation which was cut for a fabrication test.

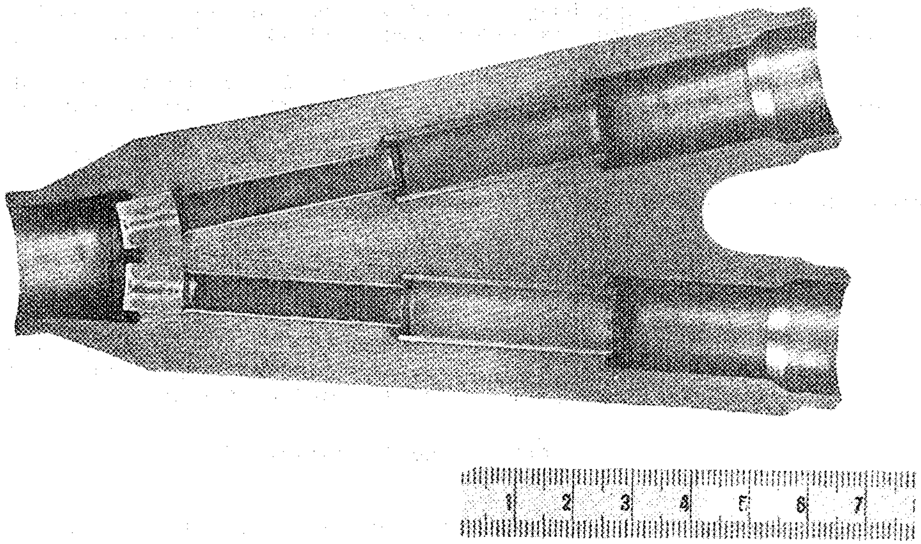


Fig. 5 Bifurcation with orifices

Orifices in Hastelloy C and austenitic tubes are brazed into a low alloy steel forging. The austenitic tubes protect the base material from erosion corrosion.

The real equalization of the pressure drop i.e. the adjustment of the correct flow, is done with throttles in the system tubes. Table 1 shows the important figures for the nominal, the shortest and the longest tube. These throttles consist of two parts, a fixed orifice and a throttling valve which is accessible during operation. The valves make it possible to adjust the flow within limits in order to obtain the specified steam temperature in each system. Fabricating tolerances especially in the inner and outer shroud or annular hot streaks are unforeseeable causes for deviations from the calculated values. Also, after plugging of a system tube these valves allow for the adjustment of the massflow of the balance of the systems of one steam generator unit.

All the valves are identical. Their pressure loss can be varied by about 10 bar. Together with 7 different orifices - producing 1,3 to 16,5 bar pressure drop - all the required pressure losses of the 40 systems of one steam generator can be achieved. The openings of the orifices are chosen such that the valves can be set to a mean position. This allows maximum correction in the case of deviation from the calculated values in both directions.

Calculations show that the steam outlet temperature of the longest tube could be lowered by 9.4 K by opening (or increased by closing) the valve. In all other systems a change of the valve position is more efficient.

Table: Characteristics of SG tubes

		100 % load			40 % load		
		nom. tube	short tube	long tube	nom. tube	short tube	long tube
Mass flow per single tube	kg/sec	0.53	0.43	0.56	0.21	0.17	0.22
% of heating surface at end of evaporation	%	81.7	82.5	80.3	78.3	79.1	78.3
Superheat at transition weld	K	26	26	28	103	95	109
Pressure loss in feedwater system tube	bar	- .5	- .7	- .5	-1.0	-1.0	-1.0
Pressure loss in heated section	bar	20.4	11.9	23.6	3.6	2.2	4.5
Pressure loss in steam syst. tube	bar	13.2	9.1	15.1	2.3	1.7	2.6
Pressure loss in throttle of single tube	bar	5.0	3.3	5.5	0.8	0.6	0.8
Pressure loss in throttle of system tube	bar	13.4	27.9	7.8	2.2	4.6	1.2

The calculated pressure drops for nominal, shortest and longest tubes are shown in the table.

Operation showed some deviations from the correct temperatures at the end of the heating surface. Correct temperatures could be achieved in all systems just by adjusting the valve positions. Results are given in [2].

Stability analysis

The previous paragraph shows how the mass flow in the different systems is adjusted according to their heat input. In this paragraph the actual analysis of the static stability described. It is done as follows: The characteristics of the system tubes and single tubes are calculated as functions of the water flow rate through a tube of nominal length with the assumption that the deviation from the nominal rate applies to all the tubes of the cylinder under consideration. A change of the water flow rate in one or more tubes causes a change of the water temperatures in these tubes which in turn changes the temperatures on the gas side. The calculation of the temperature change on the gas side takes into account the mixing of the gas.

The results show that the system is stable in all cases. The data for 40 % load, given in Fig. 6, show that stability exists also for extremely large upsets. We conclude that also smaller than the specified loads would have a stable behaviour.

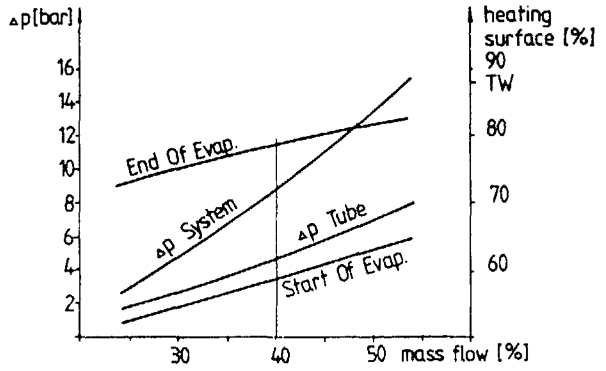


Fig. 6 Stability characteristics for 40 % load

Aspects of downhill boiling

The main difference to uphill boiling is the effect of the gravitational pressure losses. With downward flow of the water the resultant of these pressure losses is negativ and acts destabilising.

The column "shortest tube" of the table shows for 40 % load a pressure gain of 1 bar for the system tube. The pressure loss of the heated section includes a further gain of 0.6 bar. In total the gravitational effects reduce the pressure drop of the single tube by about 30 % which is not dramatic. So we can say that downhill boiling is not a drawback for the specified load range. Also removal of residual heat with reduced steam pressure is possible as calculations show. However for simplicity reasons it is always done with water recirculation.

Consideration of the dynamic stability

Tests with prototype steam generators of the French plants St. Laurent 1 and EL-4 yielded the following information about the dynamic instabilities of convectively heated once-through steam generators.

- In a tube with oscillations there is a phase shift of 180° for the water and steam flow rates.
- In general, in a given steam generator, the oscillating period and amplitude increase with decreasing load (flow rate).
- Throttles in the exit line destabilize because they act out of phase with the original disturbance.
- Throttles in the inlet line stabilize because the pressure drops which they cause are in phase with the water rate.
- The amplitudes of the steam flow rate are smaller than those of the water flow rate because for a given change of pressure drop the corresponding change of steam flow rate is smaller than that of water.

Important for the occurrence and the magnitude of the oscillation is the distribution of the pressure drop along the pipe length. Geometrical parameters are only of importance inasmuch as they influence the distribution of the pressure drop. All measures which increase the pressure drop in the liquid phase have a stabilizing effect, increasing the pressure drop in the steam phase on the other hand causes the operation to become unstable.

The comparison of the conditions of the THTR-steam generator and these test steam generators leads to the conclusion that no dynamic instabilities will occur in the operating range of 40 - 100 % load.

References

1. H.W. Fricker, "The THTR steam generator" IAEA Spec. Meeting, Winterthur (March 1987)

2. Ch. Henry, Dr. C. Elter, "Thermohydraulic Verification during THTR steam generator commissioning" IAEA Spec. Meeting, Winterthur (March 1987)