# FLOW STABILITY OF NATURAL CIRCULATION STEAM GENERATORS

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Steam generators with natural circulation have a wide range of applications such as industrial heating processes and power cycles. In steam generators unstable conditions can be the result of static instability and/or can have a dynamic nature such as density wave oscillations. To avoid mechanical damage thermo-hydrodynamic instabilities become increasingly one of the major design criteria for natural circulation boilers. In this paper the analysis of the static flow instability, namely the reverse flow, for two different types of steam generators are presented. Criteria to predict static instability were first given by Ledinegg[1]. One of the described boilers is a two-pass steam generator (see figure 1). In the second case a **H**eat **R**ecovery **S**team **G**enerator (HRSG) with a horizontal tube bank (figure 2) - which is arranged behind a gas turbine - is analysed.
The typical design of the boiler circulation system includes unequally heated tubes which are connected through headers with unheated common downcomer (see figure 1 and 2). The experience shows, that the most critical operation mode for natural circulation boilers is the hot start-up. In this case reverse flow and/or flow stagnation can occur. A static analysis can only find an answer if reverse flow under static conditions is possible, but is not able to predict whether reverse flow does actually occur. The definition of the operating conditions when reverse flow is possible, should be verified by a dynamic analysis. To make available such important data, a computer code - which is based on the SIMPLER algorithm[2] - was developed at the Institute of Thermal Engineering (ITW) at the Vienna University of Technology for the simulation of the dynamic behavior of natural circulation boilers. The mathematical model[3] for the working medium in the tubes uses the homogeneous equilibrium model for the two phase flow and applies a correction factor for the two phase pressure loss according to Friedl[4].
The aim of the work was the development of criteria to avoid the reversal of flow. In the following, we present a short summary of the case studies, which was the base to analyse a field problem for a natural circulation system similar to that shown in figure 1 and 2.

## TWO-PASS BOILER

Figure 1 shows the schematic model of the two-pass boiler. It consists of a drum, a downcomer, a header and two geometrically identical riser systems. The two riser systems are subdivided into a heated and unheated section. The unheated part of the tubes enters the drum. The two riser systems of the steam generator are heated unequally. In such a system the number of stable solutions depends on the number of branches of the tube network. It can be shown that for such systems a critical heat absorption ratio $V = \dot{q}_2 / \dot{q}_1$ exists, which is dependent on the geometry and the overall heating conditions. To determine the critical heat ratio several dynamic simulations of a warm start-up of the two-pass boiler with different heat absorption ratios and modified geometry of the boiler are done. In the following a short example for the influence of the heat absorption ratio to the stability of the boiler will be given.
Figure 3 shows as a result of the hot start-up simulation the mass flow distribution of the working medium in the tube network of the boiler. The heat absorption ratio at full load was $V$=10 and the drum pressure was 80 bar. The difference in time for the ramp-like heat input from zero to full load was 400 seconds.
The steam production in the riser system with the higher heat absorption starts approximately 20 seconds after the start of the simulation. The mass flow in the riser system 2 remains in the upward direction while the riser system 1 starts in the downward direction with relatively high mass flow. After approximately 400 seconds the flow direction changes in the lower heated tube system rapidly to

upward flow and tends, after a short peak to a much lower mass flow. After about 500 seconds both riser systems have achieved constant mass flows in the upward direction.
The result of the simulation with a small change in the heat absorption ratio from $V$=10 to $V$=11 shows figure 4. The heat flux to the higher heated riser system at full load was the same as in the previous presented calculation. In this case, the steam production in the lower heated riser system is not sufficient to change the flow direction. The working medium flows stationary in the unfavourable downward direction. This clearly demonstrates that this system is very sensible to disturbances during the start-up procedure.
On the basis of the results of this investigations it can be shown that for every natural circulation system with unequally heated risers and a common downcomer a special critical heat absorption ratio $V_{crit}$ exists. The investigations clearly indicate that such types of steam generators should be designed only in that way if the operation below the critical heat absorption ratio is possible. $V_{crit}$ must be determined for every new system configuration and heating condition. Heating conditions which exceed this critical value lead to unstable conditions with the possibility of reverse flow or almost flow stagnation. Dynamic simulations for warm start-ups have shown that natural circulation systems which are, operated too close to the critical heat absorption ratio, can shift from stable to unstable conditions during start-up or load changes. The critical heat absorption ratio is strongly dependent on the thermohydraulic behaviour of the circulation system. The modification of the flow resistance in the riser systems can help to extend the range of stable operation.

## HRSG WITH HORIZONTAL TUBE BANK

The natural circulation system shown in figure 2 tends - compared to the system in figure 1 - to be more unstable. Because of the horizontally arranged tubes the water-steam-mixture at start-up of the boiler has no favourable preferred flow direction. In this case reverse flow and/or flow stagnation can occur. Especially low pressure systems show also the tendency to dynamic flow instabilities namely density-wave, pressure-drop and parallel-channel instabilities.
Figure 2 shows the schematic model of the intermediate pressure stage of a HRSG with a horizontal tube bank of a three pressure stage waste heat boiler. It consists of a drum, a downcomer, two headers and two relief tubes with different geometry. The difference between the two relief tubes is caused by the tube length, the number of bends and the arrangement of the bends.
Figure 5 shows the result of the dynamic simulation of a hot start-up. The drum pressure during the simulation was 30 bar. At the start of the simulation the flue gas mass flow is increased in a few seconds up to 64% of the full load. This value was hold constant for 15 minutes. During the following 18 minutes the flue gas mass flow increases up to full load. The flue gas temperature before the bundle heating surface at the beginning of the simulation was 80 °C. During the simulation the flue gas temperature increased up to 280 °C at full load. With the begin of the steam production in the first layer of the bundle, the circulation of the working medium started in both relief tubes in upward direction as well as in the downcomer where the fluid flow was also directed upwards. Approximately 6.6 minutes after simulation start the mass flow in the relief tube 2 changes the direction to downward flow.
Figure 6 shows the result of the dynamic calculations for the same HRSG but with geometrical identical relief tubes. In that case, during the whole simulation, the flow direction of the working medium in both relief tubes was upward.
On the basis of the results of the investigations it can be shown that for HRSG with a horizontal tube bank in case of the using of several relief tubes their geometrical design should be identical. If the same geometry for the riser cannot be realised, the upper header must be subdivided corresponding to the number of relief tubes.

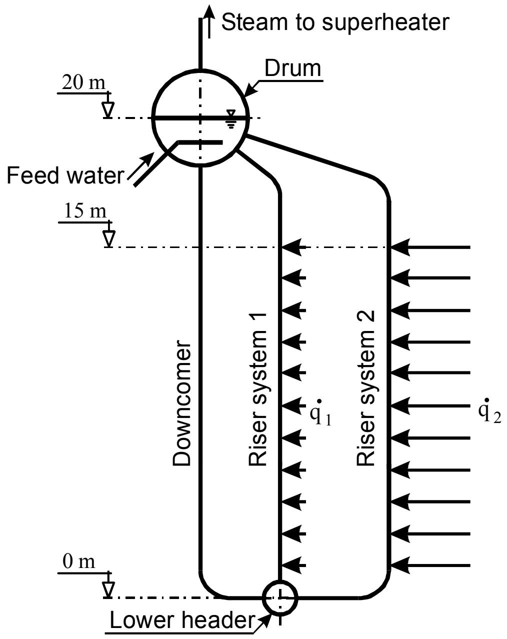


Figure 1: Two-pass boiler

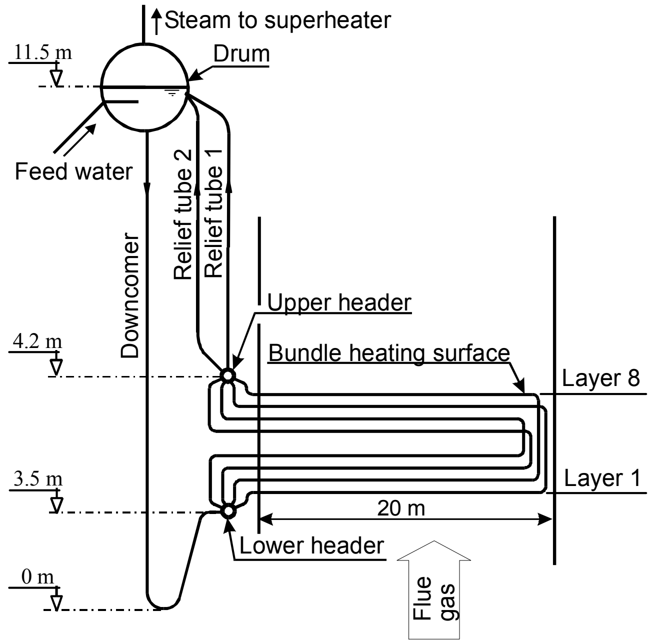


Figure 2: HRSG with a horizontal tube bank

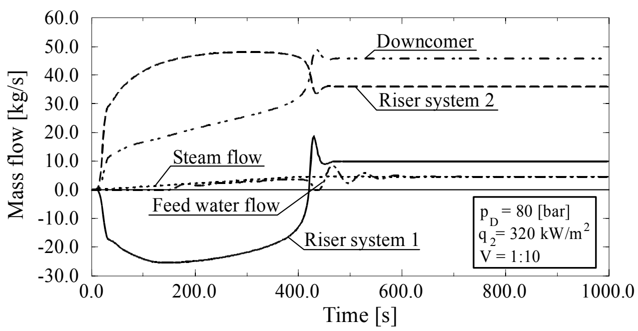


Figure 3: Mass flow in the tubes of the two-pass boiler (*V*=10)

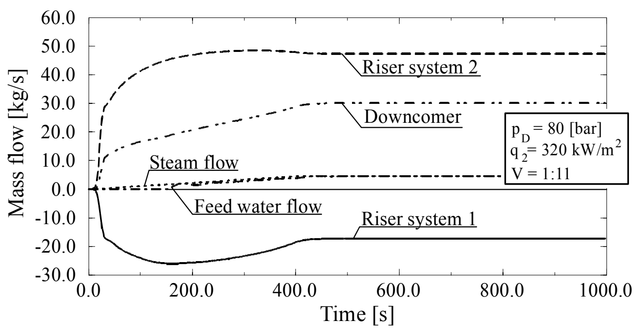


Figure 4: Mass flow in the tubes of the two-pass boiler (*V*=11)

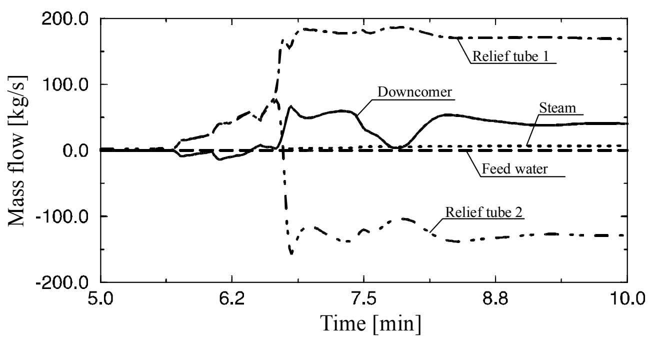


Figure 5: Mass flow in the tubes of the HRSG

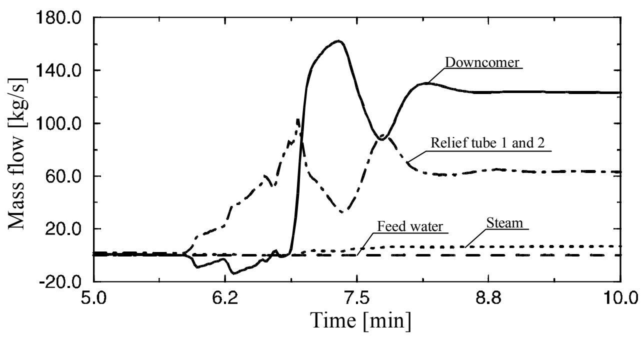


Figure 6: Mass flow in the tubes of the HRSG


1. Ledinegg, M., Instability of Flow During Natural and Forced Circulation, *Die Wärme*, Vol 61, No. 48, pp. 891-898, 1938.
2. Patankar, S. V., *Numerical Heat Transfer and Fluid Flow*, Series in Computational Methods in Mechanics and Thermal Sciences, Hemisphere Publ. Corp., Washington, New York, London, 1980
3. Walter, H., Numerical Simulation of the Dynamic Behaviour of Natural Circulation Steam Generators. *PhD Thesis*, Vienna University of Technology, 2000.
4. Friedel, L., Improved Friction Pressure Drop Correlations for Horizontal and Vertical Two-Phase Pipe Flow. *European Two-Phase Group Meeting*, Ispra, Italy, June 5 - 8, 1979, Paper E 2, pp 1 - 25.