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THERMAL-HYDRAULIC CHARACTERISTICS
OF THE PGV-1000 STEAM GENERATOR

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ABSTRACT

Horizontal steam generators are typical parts of nuclear power plants with pressure water reactor type VVER. By means of this computer program, a detailed thermal-hydraulic study of the horizontal steam generator PGV-1000 has been carried out and a special attention has been paid to the thermal-hydraulics of the secondary side. A set of important steam generator characteristics has been obtained and analyzed. Some of the interesting results of the analysis are presented in the paper.

1. INTRODUCTION

Horizontal steam generator PGV-1000 is typical part of nuclear power plants with Russian designed pressure water reactor - type VVER 1000.

The first VVER-1000 nuclear power plant was put into operation in 1980 and there are currently 19 units operating with 76 steam generators PGV-1000 (1000 MW) and two nuclear power plants with 8 PGV-1000 are under construction in the Czech Republic. In the period from 1986 to 1991, serious deficiencies on 24 horizontal steam generators at six VVER 1000 nuclear power plants were detected. The identification of the causes of deficiencies has shown that secondary side fluid flow, primarily flow influence on the mineral distribution, plays important role in the damage processes. In order to optimize flow distribution on the secondary side and to minimize mineral concentration in failure sensitive areas the multidimensional thermal-hydraulics phenomena in the steam generator secondary side should be analyzed in detail.

Thermal-hydraulic behavior of horizontal steam generator is very different from the vertical U-tube steam generator which has been extensively studied for many years. Only limited experimental data on the behavior of horizontal steam generators is available and

particularly on the natural circulation in the secondary side. Thus more information is needed. The study in this field proceeds in both directions - experimental and theoretical using mathematical modelling. Experimental tests using experimental facilities have been performed in Finland (PACTEL facility) and in Hungary (PMK-2 facility), experimental tests at operating nuclear power plant units in Russia [1], [2], [3]. Detailed mathematical models for the study of the horizontal steam generators behavior have been developed in Russia and in the Czech Republic [4], [5]. Design principles of the Czech computer program - the nodalization which has been used and the physical methods applied to calculations will be shortly described.

A detailed thermal-hydraulic and thermodynamic study of the horizontal steam generator PGV-1000 for the Czech nuclear power plant Temelin has been carried out using the developed computer program. A wide range of calculations has been performed and a set of important steam generator characteristics has been obtained. The most important of them are presented in the paper.

2. COMPUTER PROGRAM FOR STEADY STATE THERMAL HYDRAULIC ANALYSES OF THE STEAM GENERATOR PGV-1000

2.1. Computer Program Capabilities

The computer program is capable to analyze :

1. *Steam generator primary side hydraulics*
    -   primary side flow distribution in tube bundles and velocity distribution in collectors;
    -   pressure drop distribution and the total primary side pressure drop.

2. *Heat exchanger behavior*
    -   heat transfer for various situations in the tube and shell side (low level and the effect of tube bundle uncovery is taken into account);
    -   multidimensional heat flux distribution, total heat flux transferred through heat exchanger tubes (steam generator heat power);
    -   primary side fluid temperature distribution - fluid and tube temperature profiles (along the tubes);
    -   outlet mixed mean temperature of the primary side fluid;
    -   steam outlet temperature and the temperature of the steam-water mixture at the shell side.

3. *Steam generator secondary side thermal-hydraulics and thermodynamics*
    -   average circulation rate for the cases with the level above the top of the tube bundles;
    -   3-D void fraction distribution in the shell side;
    -   steam and water volumes under the level, steam generator water mass inventory;

- mass redistribution under the perforated sheet and minimal thickness of the steam layer;
- secondary side pressure (for the plant operation in Mode that maintains a constant mean coolant temperature in the primary system);
- steam flow rate;
- secondary side pressure drops distribution and the total secondary side pressure drop.
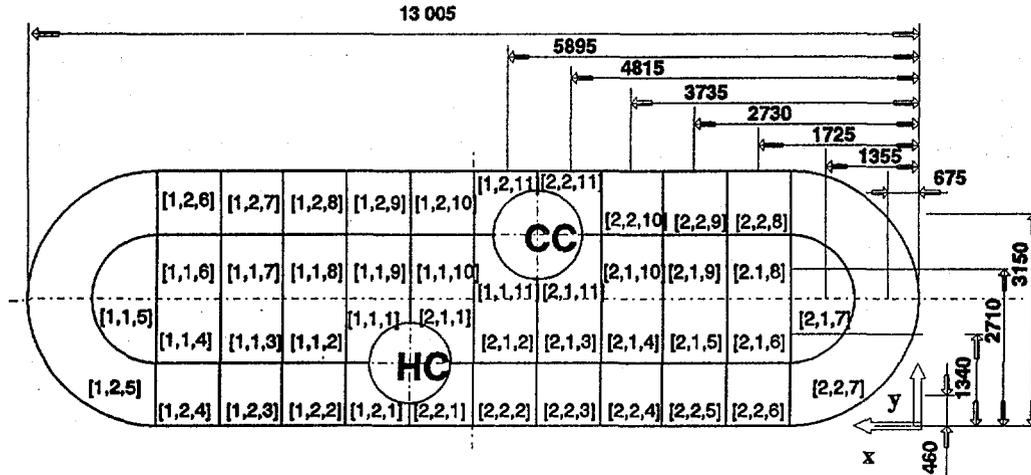

Figure 1:   Tube Bundles Nodalization [horizontal direction]. Dimension [mm].
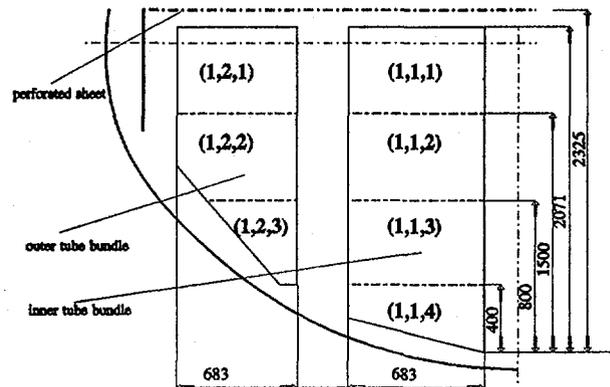

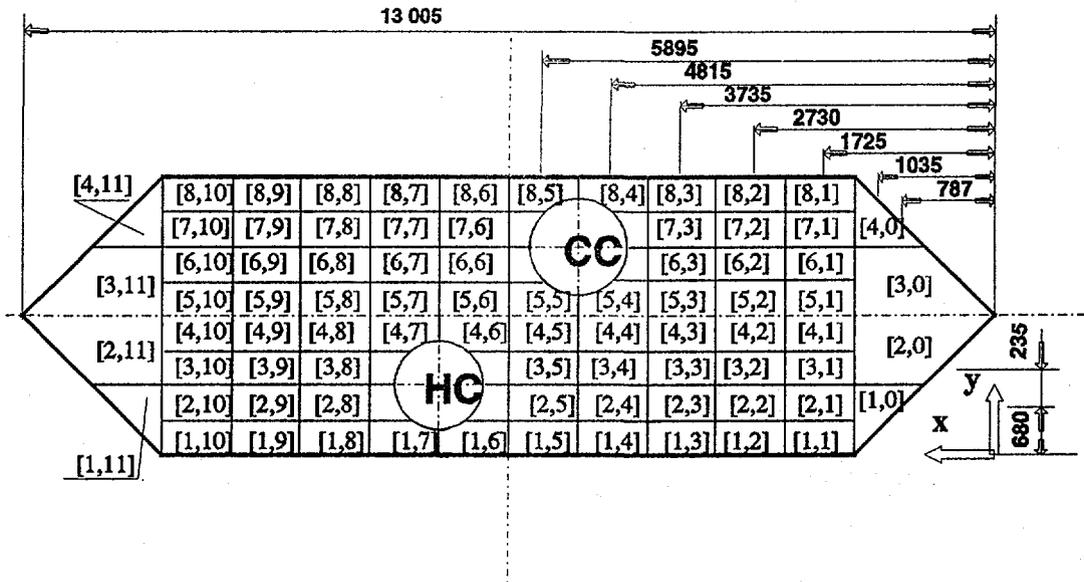**Figure 2:**   Tube Bundles Nodalization [vertical direction]. Dimension [mm].

13 005

5895
4815
3735
2730
1725
1035
787

[4,11]

[8,10]	[8,9]	[8,8]	[8,7]	[8,6]	[8,5]	[8,4]	[8,3]	[8,2]	[8,1]
[7,10]	[7,9]	[7,8]	[7,7]	[7,6]		CC	[7,3]	[7,2]	[7,1]	[4,0]
[6,10]	[6,9]	[6,8]	[6,7]	[6,6]			[6,3]	[6,2]	[6,1]
[5,10]	[5,9]	[5,8]	[5,7]	[5,6]	[5,5]	[5,4]	[5,3]	[5,2]	[5,1]	[3,0]
[4,10]	[4,9]	[4,8]	[4,7]	[4,6]	[4,5]	[4,4]	[4,3]	[4,2]	[4,1]	[2,0]
[3,10]	[3,9]	[3,8]			[3,5]	[3,4]	[3,3]	[3,2]	[3,1]
[2,10]	[2,9]	[2,8]	HC		[2,5]	[2,4]	[2,3]	[2,2]	[2,1]	[1,0]
[1,10]	[1,9]	[1,8]	[1,7]	[1,6]	[1,5]	[1,4]	[1,3]	[1,2]	[1,1]

[3,11]   [2,11]   [1,11]

235   680

y   x

Figure 3:   Perforated Sheet Division. Dimension [mm].

2.1   Simulation Methods

For the calculation of primary side flow distribution the heat exchanger is divided into groups of tubes as is shown in Fig.2. Average flow velocity is evaluated for each group. The primary results of the calculation are the velocity distribution in the header and the flow velocities in the tubes. Model representation of the primary side pressure drops takes into account pressure drops in the inlet and outlet tubes connecting the steam generator with the hot and cold legs of the circulation loops, in both collectors and in the heat exchanger tubes.

The nodalization of the heat exchanger tube bundles for steady state thermal analysis corresponds to that shown Fig.1,2. The iterative method of calculation is based on thermal balance. The calculation is performed for every node separately and a global thermal balance is checked. The main result is the heat flux distribution in the steam generator shell side. The global heat flux is the essential parameter for the assessment of secondary side pressure and steam flow rate. The program takes into consideration two possibilities - the steam generator is above the top of tube bundles and the steam generator level is under the top of tube bundles with some tube uncovered.

To determine the average value of the circulation rate a simple flow diagram is assumed. Two phase mixture rises up through the area in tube bundles, above the tube bundles steam and water are separated. The water flows back in the downcomer and in the free space between the tube bundles.

For the assessment of void fraction distribution the region between steam generator

bottom and upper tube rows of heat exchanger is divided in vertical direction into layers of equal height of 50 mm. The heat flux into an arbitrary volume is obtained from the heat exchanger calculation. The feedwater distribution is taken into account. The calculation of the void fraction begins in the bottom of the steam generator and proceeds step by step over the layers to the top of the region. Two different methods have been developed for this calculation. The first method is based on the circulation rate assessment and it is applied to cases where the average level is above the top tube bundles. The second method is based on the theory of free bubbles rising through liquid by buoyancy and it is used for all cases with the level under the top of tube bundles. The second method of void fraction assessment does not take into consideration the circulation of the fluid. In the comparison with the first one the second method gives slightly conservative results in the direction of higher void fraction, especially in the close vicinity of the hot collector.

For the cases with the level above the top tube bundle, the effect of perforated sheet is simulated. Hydrodynamic processes in the region between upper rows of the tube bundles and submerged perforated sheet depend on perforated sheet design, especially on the degree of the perforation and on the height of the perforated sheet rim. The goal of the simulation is to assess the steam flow rate from more loaded zones to the less loaded regions and to determine the thickness of the steam layer in different locations bellow the perforated sheet. The nodalization of this region corresponds to the perforated sheet division, which is shown in Fig.3.

The complete mathematical model for the steam generator PGV-1000 thermal-hydraulic study is formulated in [4], [5].

Only a partial verification of the model could be performed. Some results of void fraction calculations were compared with experimental data obtained by Russian organization Gidropress and published in [3], [6]. The result of calculations show a good compliance with experimental results.

3.   STEAM GENERATOR PGV 1000 THERMAL HYDRAULIC STUDY

A detailed thermal-hydraulic a thermodynamic study of the PGV-1000 horizontal steam generator for the Czech nuclear power plant Temelin has been carried out and a great amount of interesting information has been obtained. The special attention has been paid to the secondary side analysis, primarily to the mixture level profile, 3-D void fraction distribution and to the distribution of the heat flux transferred to the secondary medium under different operation conditions.

Some important steam generator characteristic parameters have been investigated, for example:
- secondary side water and steam volumes and masses as functions of load at constant pressure and as functions of pressure at constant load;
- 3-D distribution of the void fraction as a function of load at constant pressure and as a function of pressure at constant load;

- the steam generator level profile as a function of load and a function of pressure;
- the average void fraction as a function of steam generator load and secondary pressure;
- the average level as a function of load for constant pressure and as a function of pressure for constant load;
- the perforated sheet pressure drop as a function of load.

Some results of the PGV 1000 thermal-hydraulic investigations are given in Figures 4 to 11.

In the presented calculations the values of parameters as volumetric flow rate, primary side pressure, the feed-water flow rate, feed water temperature and the steam generator level correspond to nominal operating conditions. Under these conditions the vapour volume V'' and the water volume V' under steam generator level as functions of the heat power Q (steam generator load) are shown in Figures 4, 5. As evident from Figure 4, the vapour volume V'' is proportional to Q for a given (fixed) pressure p. The increase is higher for the low pressure than for the high pressure. The water volume V' in Figure 5 decreases proportionally with increasing Q.

The vapour volume V'' and the water volume V' under the steam generator level as functions of secondary side pressure are given in Figures 6,7. It can be observed from Figure 6 that the vapour volume V'' decreases with increasing pressure p for fixed heat power Q. The decrease is higher for higher heat power. The water volume V' in Figure 7 increases with increasing of pressure. It is evident that the vapour volume - power relationship has twice as high influence than the relationship between the vapour volume and pressure. This fact should be taken into consideration when setting the steam generator measurement and control system is carried out.

The water mass inventory M' which is one of the most important parameters of the steam generator is shown as a function of load in Figure 8 and as a function of secondary side pressure in Figure 9. The water inventory in the horizontal steam generator is higher than in the vertical one. This is important with respect to steam generator dynamic behavior and water level fluctuation during normal operation. The effect of the steam generator water inventory is one of the factors influencing the steam generator operational reliability and plant safety.

The vapour mass M' under the steam generator level as a function of total heat power Q and secondary side pressure p is given in Figures 10 and 11.

4.   SUMMARY

Using the 3-D computer program the investigation of the thermal-hydraulic behavior of the horizontal steam generator for the VVER 1000 nuclear power plant has been carried out. The detailed information about multidimensional two-phase flow in the steam generator shell side has been obtained. This includes void fraction distribution and the characteristics of natural circulation and of the heat transfer and swelled level dynamics.

The detailed knowledge of these parameters may provide information needed for the efficient nodalization of the horizontal steam generator in safety analysis codes for the setting of the water level control and for the safety enhancement of the VVER 1000 nuclear power plants.

5. NOMENCLATURE

p	MPa	Pressure (secondary side)
PN	MPa	Nominal pressure (secondary side)
Q	MW	Heat power
QN	MW	Nominal heat power

6. REFERENCE

[1] *International Seminar on Horizontal Steam Generator Modelling, Vol.I., Vol.II.*, Proc., Lappearanta University of Technology, Finland, (1991).

[2] *Second International Seminar on Horizontal Steam Generator Modelling*, Proc., Lappearanta University of Technology, Finland, (1993).

[3] *Third International Seminar on Horizontal Steam Generator Modelling*, Proc., Lappearanta University of Technology, Finland, (1994).

[4] Doubek,M., Ubra,O.: *Steam Generator PGV-1000, Steady State*, CTU Report, Z-490, CTU, Dept.of Thermal and Nuclear Power Plants, Prague, (1994).

[5] Doubek,M., Ubra,O.: *Computer Program for Horizontal Steam Generator Thermal-hydraulic Analysis*, Proc. New Trends in Nuclear System Thermohydraulics, Vol.I., 751-760, Italy (1994).

[6] Vasiljeva, A.G.,Dmitrijev, A.I.: *Issledovanije gidrodinamiky parogeneratora PGV-1000*, Elektriceskije Stanciji 6, Pg.19-23, Fig.2, (1987).   (in Russian)
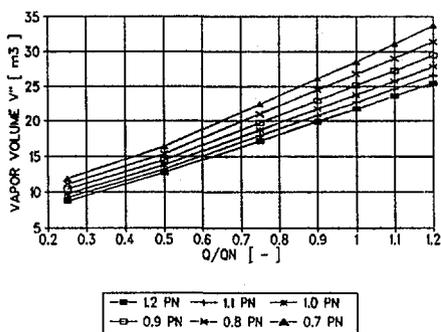
7. FIGURES

Figure 4 :
Vapour volume under steam generator level as a function of load
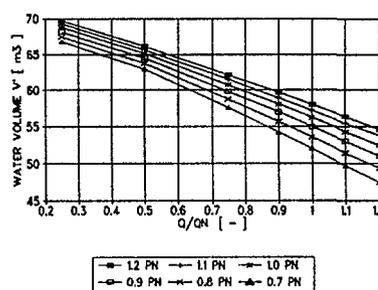(nominal heat power QN = 750 MW)

Figure 5 :
Water volume under steam generator level as a function of load
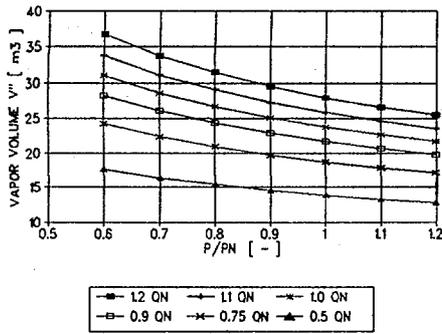(nominal heat power QN = 750 MW)

Figure 6 :
Vapour volume under steam generator level as a
function of secondary side pressure
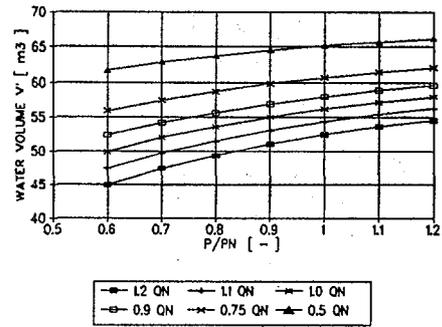(nominal pressure PN = 6,27 MPa)

Figure 7 :
Water volume under steam generator level as a
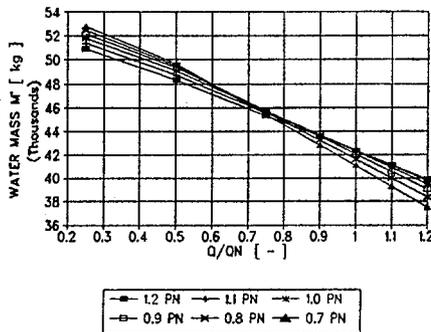function of secondary side pressure
(nominal pressure PN = 6,27 MPa)

Figure 8 :
Steam generator water inventory as a function of
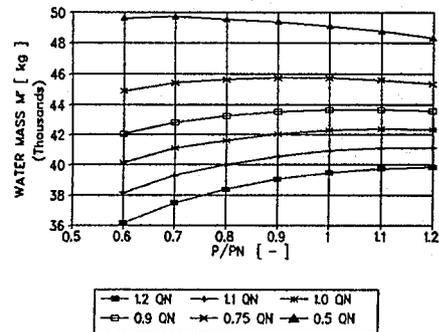load
(for 6 different secondary side pressure)

Figure 9 :
Steam generator water inventory as a function of
secondary side pressure
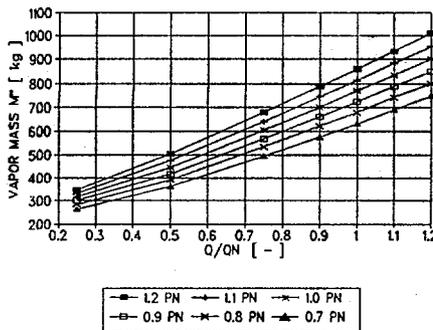(nominal pressure PN = 6,27 MPa)

Figure 10 :
Vapour mass under steam generator level as a
function of load
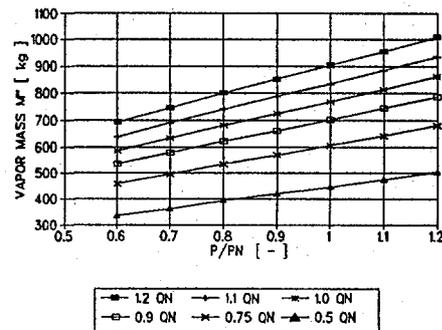(nominal heat power QN = 750 MW)

Figure 11 :
Vapour mass under steam generator level as a
function of secondary side pressure
(nominal pressure PN = 6,27 MPa)