

NUMERICAL DISCRETIZATION ANALYSIS OF A HTR STEAM GENERATOR MODEL FOR THE THERMAL-HYDRAULICS CODE TRACE

by

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For future high temperature reactor projects, *e. g.*, for electricity production or nuclear process heat applications, the steam generator is a crucial component. A typical design is a helical coil steam generator consisting of several tubes connected in parallel forming cylinders of different diameters. This type of steam generator was a significant component used at the thorium high temperature reactor. In the work presented the temperature profile is being analyzed by the nodal thermal hydraulics code TRACE for the thorium high temperature reactor steam generator. The influence of the nodalization is being investigated within the scope of this study and compared to experimental results from the past. The results of the standard TRACE code are compared to results using a modified Nusselt number for the primary side. The implemented heat transfer correlation was developed within the past German HTR program. This study shows that both TRACE versions are stable and provides a discussion of the nodalization requirements.

Key word: numerical stability analysis, TRACE, steam generator

INTRODUCTION

The high temperature reactor (HTR) is a viable option for electricity production (*e. g.*, SMR) or even more important for process heat generation. Helium outlet temperatures of 750-850 °C enable the HTR to capture an important share of the process heat market. Thus, the steam generator (SG) is a key component. Westinghouse Electric Germany GmbH is the legal successor of the company HRB (Hochtemperatur-Reaktorbau GmbH) which generated HTR know-how. Since the commissioning of the thorium high temperature reactor (THTR-300) requirements for codes and techniques changed. The modeling of components, *e. g.*, the steam generator, with nodal thermal-hydraulic codes is one aspect of this update.

Westinghouse Electric Germany GmbH is one of the German participants of the code application and maintenance program (CAMP) of the United States Nuclear Regulatory Commission (U.S. N.R.C). The purpose of this program is the validation and qualification of system codes, *e. g.*, TRACE (TRAC/RELAP Advanced Computational Engine) [1] which is still under development.

TRACE has been designed to perform best-estimate analyses of loss-of-coolant accidents (LOCA), operational transients, and other accident scenarios in pressurized light-water reactors (PWR) and boiling light-water reactors (BWR) [2]. The adaptation of TRACE for steam generators of high temperature reactors is done in the frame of this study following these steps:

- analysis of thermal-dynamics,
- modeling of geometry, and
- validation by experimental results

For validation, the results are compared to experimental data of the THTR-300 steam generator.

Thorium high temperature reactor

In 1971 the THTR-300 was built by BBC/HRB (Brown, Boveri & Cie AG/Hochtemperatur-Reaktorbau GmbH) in Hamm-Uentrop/ Germany. Westinghouse Electric Germany GmbH is one of the legal successors of the former German HTR companies and it maintains the knowledge and experience of this technology.

The THTR-300 core outlet temperature was 750 °C. The thermal power of 750 MW was transferred to the secondary circuit by six helical tube type heat exchangers which were arranged annular around

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the reactor core. The electrical power was 308 MW. The THTR-300 was operated for 5 years and then shut down and decommissioned for political reasons [3]. The THTR-300 technology was qualified by a wide R&D program. The operation of the THTR-300 proved that a commercial application of this technology represents no technological risk for the potential customer. A cutaway view of the THTR-300 is shown in fig. 1.

Helium flow

The cold helium enters the reactor core at the top, passes through the pebble bed and leaves it at the bottom through various channels in the bottom reflector to the bottom of the steam generators. The flow direction within the steam generators is from the bottom to the top. On the way the helium passes the helix type tubes of reheater (RH) and the two high pressure bundles (HP) which consist of super-heater (SH), evaporator (EVAP), and economizer (ECO).

At the top of the steam generator the helium flow enters the steam generator annulus by a *u*-turn, flows through the blower and then outside the liner to the bottom of the steam generator. There it enters the bottom of the reactor annulus and flows outside the graphite reflector to the top where it enters the core region again.

Steam generator design

The helical coil tube type steam generators of the THTR-300 consist of a shell and three tube bundles inside. The small bundle on the bottom of the SG, which is shown in fig. 2 is the reheat section bundle. In this

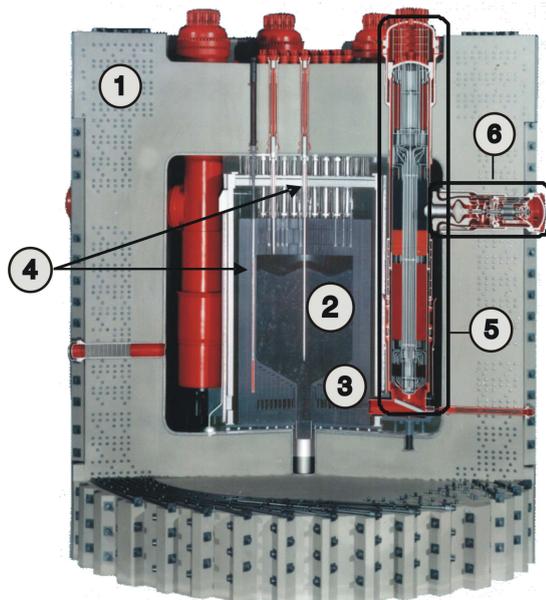


Figure 1. THTR-300

1 – pre-stressed concrete reactor vessel (PCRV), 2 – the reactor core, 3 – ceramic core structures, 4 – absorber rods, 5 – the steam generators, 6 – the helium circulators

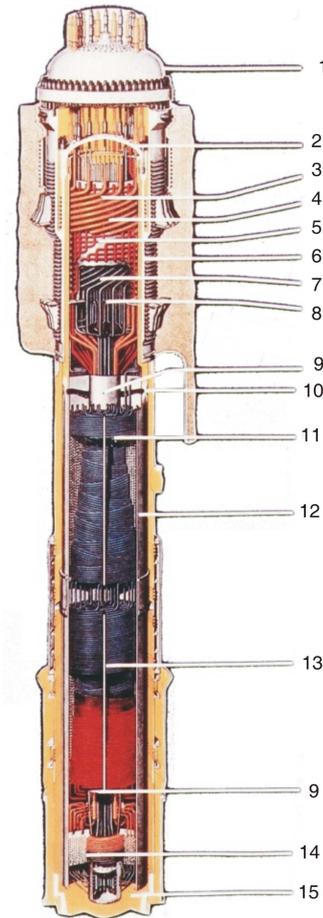


Figure 2. Steam generator cutaway view

1 – outer closure, 2 – inner closure, 3 – RH steam outlet, 4 – expansion compensation zone, 5 – HP steam outlet, 6 – PCRV penetration, 7 – RH steam inlet, 8 – feed-water inlet, 9 – central tube, 10 – helium outlet, 11 – HP-I-bundle, 12 – outer shroud, 13 – HP-II-bundle, 14 – RH-bundle, 15 – helium inlet

study, the focus is on the high pressure section and the reheat section will not be considered. Due to manufacturing reasons, there exist two high pressure bundles above the RH-section which include SH, EVAP, and ECO. The helical tubes of the thermal expansion modulus are located on top of the steam generator.

The thermal power of one steam generator is 128 MW, whereby the two high pressure bundles transfer 111 MW and the RH bundle transfers 17 MW (design data) [4].

On the secondary side, water enters the helical tubes on top of the HP-bundle. The water flow is downwards. First, the water will be preheated in the economizer, then evaporated and at last superheated before leaving the steam generator.

The HP-bundles of the steam generator consist of 80 tubes divided in 15 tube cylinders. Each tube of the same tube cylinder has an identical geometry, *e. g.*, length and inclination. Tubes of adjacent cylinders are coiled in the opposite direction. The main geometric data of the two high pressure bundles are given in tab. 1.

Table 1. Geometric data of THTR-300 SG bundle

No.	D [mm]	Parallel	l [m]	ε [°]
1	858.3	4	155.3	3.06
2	935.0	4	169.2	2.81
3	1011.7	4	182.9	2.60
4	1088.3	4	196.7	2.41
5	1165.0	4	199.5	2.38
6	1241.7	5	190.2	2.50
7	1318.3	5	190.7	2.49
8	1395.0	5	191.2	2.48
9	1471.7	6	187.8	2.53
10	1548.3	6	186.6	2.55
11	1625.0	6	195.9	2.42
12	1701.7	6	194.3	2.44
13	1778.3	7	194.5	2.44
14	1855.0	7	191.7	2.48
15	1931.7	7	199.5	2.38

In the five columns the tube cylinder No. is given; D is the mean diameter of the cylinder, l the length of the tube and ε the inclination angle. Figure 3 shows the helix of one high pressure bundle during manufacturing with a total height of around 4 m.

TRACE – model

TRACE is a best-estimate thermal-hydraulic reactor system code which is being developed by the U.S. Nuclear Regulatory Commission (NRC). The

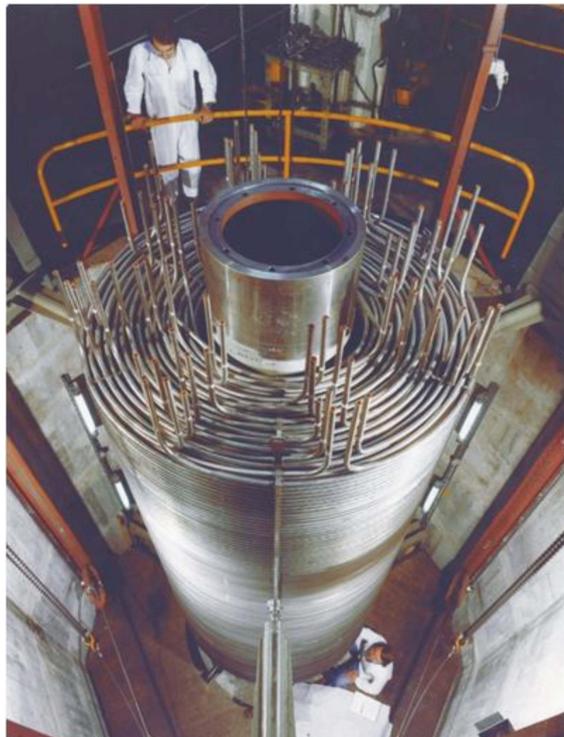


Figure 3. Manufacturing of THTR-300 steam generator helix bundle

TRACE code includes models like multidimensional two-phase flow, generalized heat transfer, heat conduction, no-nequilibrium thermodynamics, level tracking, reflood, and reactor kinetic models. The code architecture is completely modular [5]. TRACE is still under development. TRACE Version 5 Patch 1 (T5P1) is used.

Creating the model in TRACE is a crucial step. On the one hand the model has to be as exact as possible; on the other hand simplifications have to be done due to geometric limitations of the code. A 3-dimensional helix cannot be modeled in TRACE.

Symbolic nuclear analysis package

The TRACE model is being created with the symbolic nuclear analysis package (SNAP) version 1.2.0. SNAP is a graphical user environment designed to assist the NRC code user in all aspects of input model development [6].

Model description

Within the scope of the development of a TRACE model for transient calculations this study is done for the validation of TRACE for helium cooled high temperature reactors. Due to the different geometry of the HP-bundles and the RH-bundle, just the HP bundles are investigated and the RH-bundle as well as the connecting tubes are not considered in this study.

The operating condition is full load and the thermal-hydraulic parameters and boundary conditions of the model are shown in tab. 2.

There are 80 helical tubes at 15 tube cylinders in one steam generator. In this TRACE model, the helix is simplified to angular tubes. Figure 4 shows the simplification principle of helical tubes. The helix is unwound to a straight tube under a specified angle.

Figure 5 illustrates the modeling principle. The TRACE model consists of a water FILL component (1), a helical tube (2), and the steam BREAK component (3) on the left side. In the middle is the HEAT STRUCTURE component (4), and on the right side are Helium FILL (5), shell tube (6), and Helium BREAK (7) component.

The TRACE Model which was used for the calculations consists of 4 groups of tube cylinders with the same amount of parallel tubes for the water/steam

Table 2. Thermal-hydraulic conditions [4, 7]

v_{He}	Helium inlet temperature (HP-bundle)	667 °C
\dot{m}_{He}	Helium mass flow	50 kg/s
p_{He}	Helium outlet pressure	3.81 MPa
v_{H_2O}	Water inlet temperature	180 °C
\dot{m}_{H_2O}	Water mass flow	41 kg/s
p_{H_2O}	Steam outlet pressure	19.6 MPa

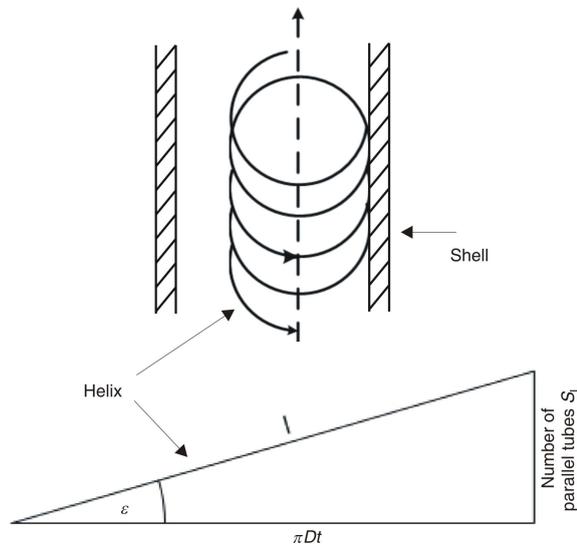


Figure 4. Simplification principle of helical tube

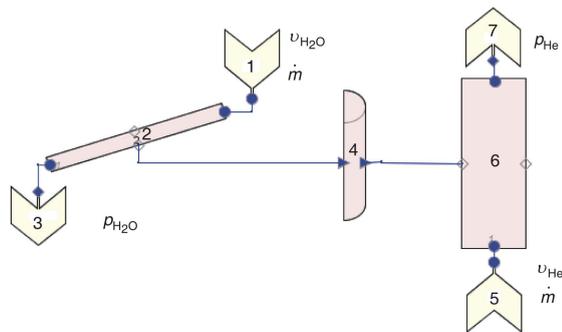


Figure 5. Simplified TRACE model

side and a shell tube for the helium side. Primary and secondary sides are connected by HEAT STRUCTURES. FILL and BREAK components are used to apply the desired coolant-flow and pressure boundary conditions. The model is shown in fig. 6. The discretization analysis is done for 25, 50, 100, 200, 300, and 400 nodes of each tube with respective average node length of 7.6 m, 3.8 m, 1.9 m, 1.0 m, 0.6 m, and 0.5m for a total average tube length of 190.6 m.

VALIDATION AND EVALUATION OF APPROPRIATE NU-CORRELATIONS

In this chapter the investigated Nusselt numbers are described and the results are compared to experimental data.

Heat transfer correlations

In the standard TRACE code the following Nusselt number is implemented

$$Nu = \frac{f_c (Re - 1000) Pr}{1 + 12.7 \sqrt{f_c} (Pr^{0.66} - 1)} \quad (1)$$

with

$$f_c = \frac{0.5}{[1.59 \log_e (Re - 3.28)]^2} \quad (2)$$

This equation is valid for Reynolds numbers higher than 1000 and Prandtl numbers higher than 0.15 [8].

The analysis of the discretization of the TRACE model is also done with a modified TRACE code. The modification of the code is done in the primary side (Helium side) heat transfer correlation. The secondary side (Water/Steam side) heat transfer correlations have not been modified. These interfacial heat transfer coefficients are dependent upon the flow regime selected by the code [2].

The investigated Nusselt number was developed within the past German HTR program. The validity extend was not written down in available reports [4]. In a further study comparing the results of 6 Nusselt numbers for the primary side of HTR steam generators Nu4V is giving most accurate results [9]. This Nusselt number is given by eq. 3

$$Nu_{V4} = 0.1135 (f_a Re)^{0.714} \sqrt[3]{Pr} \quad (3)$$

with a flow factor f_a taking into account the helix geometry of the heat transfer bundles

$$f_a = \frac{x_T}{x_T \sqrt{1 + \frac{x_L^2}{16x_T^2}}} \frac{1}{0.927} \quad (4)$$

where x_L is the non-dimensional longitudinal pitch/ d and x_T – the non-dimensional transversal pitch/ d .

RESULTS

Figure 7 shows the axial temperature profile of the standard TRACE code (T5P1) with a discretization of 300 nodes. The helium inlet temperature is 667 °C and its outlet temperature is 293 °C. The water inlet temperature is 180 °C and the steam outlet temperature is 554 °C. 60% of the heating surface is used for pre-heating the water. Evaporation takes place between abscissas 60% and 75% of the heating surface followed by the superheating section.

For the investigation of the influence of the discretization the temperature difference is applied to a reference value. This reference value is the calculated temperature in degree Kelvin of the finest discretization (400 nodes)

$$\Delta \bar{v}_{He} = \frac{v_{He}^{xnodes} v_{He}^{400nodes}}{v_{He}^{400nodes}} \quad (5)$$

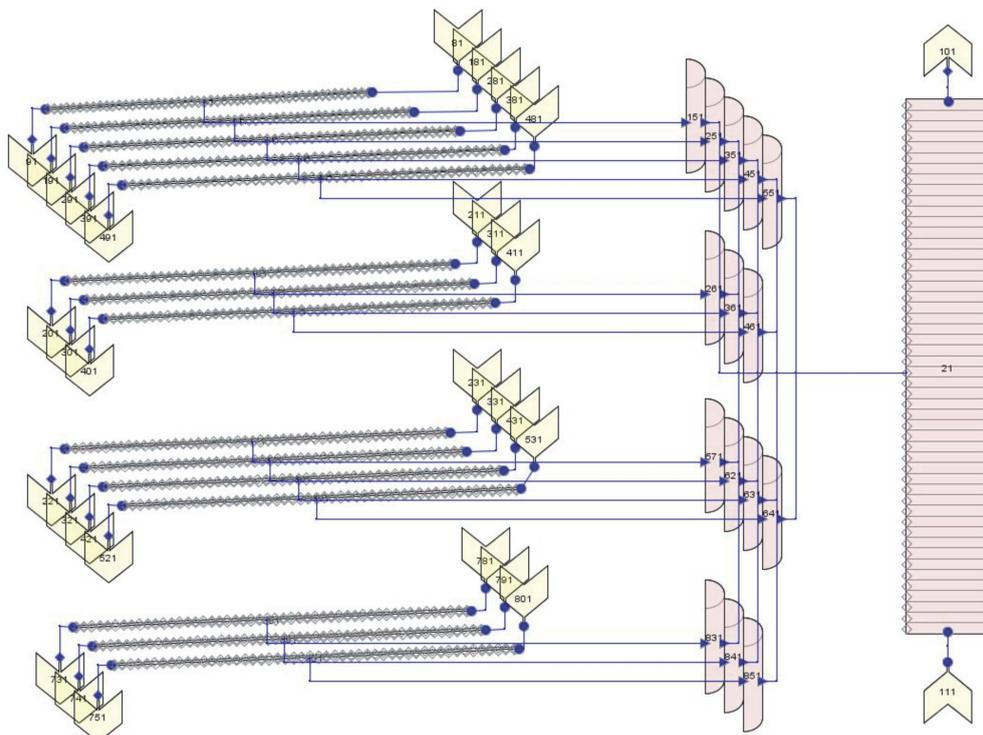


Figure 6. Trace model of THTR-300 steam generator

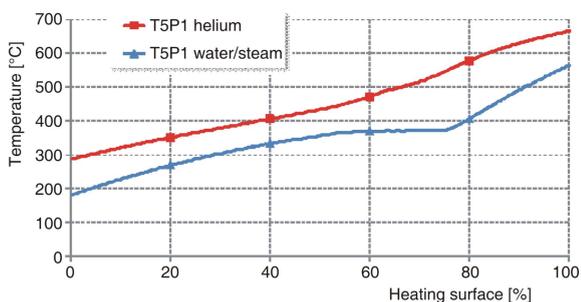


Figure 7. Axial temperature profile of standard TRACE code

$$\Delta \bar{U}_{H_2O} = \frac{U_{H_2O}^{xNodes} - U_{H_2O}^{400Nodes}}{U_{H_2O}^{400Nodes}} \quad (6)$$

The effect of the discretization is shown in fig. 8 and fig. 9 for the standard TRACE Code and in fig. 10 and fig. 11 for the modified TRACE Code. The normalized helium temperature differences compared to the finest discretization of 400 nodes are up to -2.2% for the standard TRACE code and up to -2.6% for the modified TRACE code. The normalized water/steam temperature differences compared to the finest discretization of 400 nodes rise from 0.9% to -2.6% for the standard TRACE code and from 0.9% to -3.3% for the modified TRACE code.

The maximum temperature discrepancy can be observed in the phase change region. For the helium temperature differences there are two peaks, one at the starting point of evaporation and one at the end point.

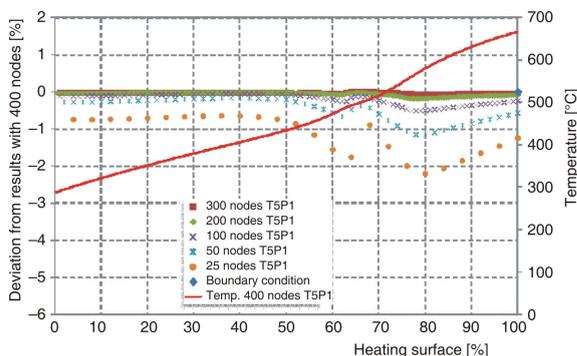


Figure 8. Deviation of helium temperature from the results of the finest discretization model (400 nodes) plotted vs. the heating surface for the standard TRACE code

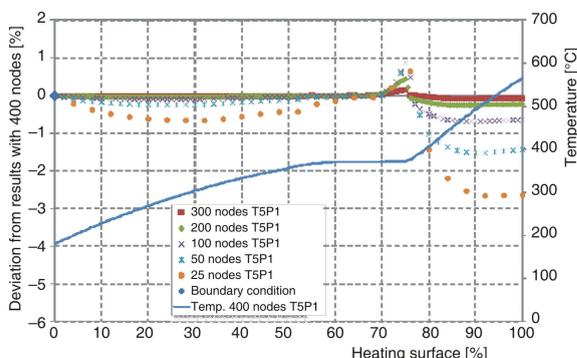


Figure 9. Deviation of water/steam temperature from results of finest discretization model (400 nodes) plotted vs. the heating surface for the standard TRACE code

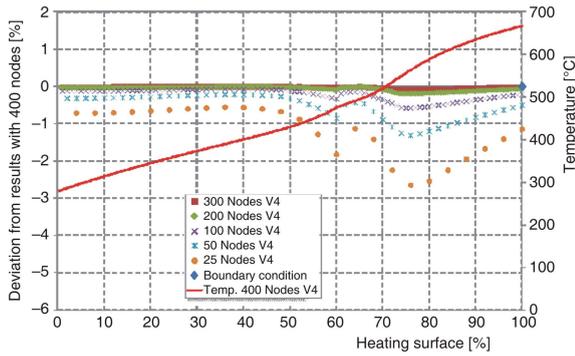


Figure 10. Deviation of helium temperature from the results of the finest discretization model (400 nodes) plotted vs. the heating surface for the modified TRACE code

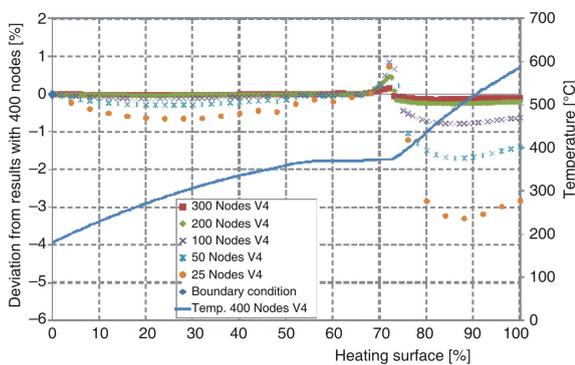


Figure 11. Deviation of water/steam temperature from results of finest discretization model (400 nodes) plotted vs. the heating surface for the modified TRACE code

For the water/steam side at the end region of evaporation first the normalized temperature differences cross the *x*-axis to positive values and then to negative differences.

One of the THTR-300 steam generators was instrumented with thermocouples. These experimental

data can be used for validation. The measured steam outlet temperature data were analyzed and evaluated. For full load of the steam generator an average value of 563 °C was identified [7] but there is no experimental data available for the helium outlet temperature at the top of the high pressure bundle. For comparison, a previous calculation result will be used. The helium outlet temperature should be 245 °C [10]. This is in agreement with the measured helium temperature of the blower inlet where 248 °C are measured [7].

In fact, the theoretical design data did not match the experimental data exactly. The design data of transferred power of the HP-bundles is 111 MW. Due to the measured temperatures an experimental power of 109 MW was calculated by using the equation

$$P = c_{p_He} \dot{m}_{He} \Delta T_{He} \quad (7)$$

with $c_p = 5195 \text{ J/kgK}$ [11] and $\dot{m} = 50.0 \text{ kg/s}$ [4] for helium.

The TRACE version with the standard Nusselt number has the lowest heat transfer. It calculates the highest helium outlet temperature and the lowest steam outlet temperature. The TRACE version with the V4 Nusselt number shows the highest heat transfer with respect to the lowest helium outlet temperature and the highest steam outlet temperature. Table 3 shows the results of the TRACE calculations for the different discretization compared to experimental data of power, helium and steam outlet temperatures as well as the helium and steam pressure drops.

The equation for estimating the error of heat transfer is

$$Error = \frac{P_{\text{calculation}} - P_{\text{experiment}}}{P_{\text{experiment}}} \cdot 100\% \quad (8)$$

TRACE underestimates the outlet temperature, the temperature difference and the power, respec-

Table 3. TRACE results with input data of tab. 2; helium mass flow = 50 kg/s, helium inlet temperature = 667 °C, water mass flow = 41 kg/s, and water inlet temperature = 180 °C

	Discretization	Transferred power	Helium outlet temp.	Helium pressure drop	Steam-outlet temp.	Water pressure drop
	(nodes)	[MW]	[°C]	[MPa]	[°C]	[MPa]
Experiment		109.61	245	$3.8 \cdot 10^{-2}$	563	2.02
T5P1	25	96.13	296.9	$3.8 \cdot 10^{-2}$	543.4	1.83
	50	97.22	292.7	$3.8 \cdot 10^{-2}$	553.6	1.94
	100	97.89	290.1	$3.9 \cdot 10^{-2}$	560.2	1.96
	200	98.23	288.8	$3.9 \cdot 10^{-2}$	563.6	1.98
	300	98.36	288.3	$3.9 \cdot 10^{-2}$	564.9	1.98
	400	98.42	288.1	$3.9 \cdot 10^{-2}$	565.6	1.98
V4	25	98.14	289.1	$3.8 \cdot 10^{-2}$	562.6	1.91
	50	99.40	284.3	$3.8 \cdot 10^{-2}$	574.8	2.02
	100	100.06	281.8	$3.9 \cdot 10^{-2}$	581.5	2.04
	200	100.41	280.4	$3.9 \cdot 10^{-2}$	585.2	2.05
	300	100.54	279.9	$3.8 \cdot 10^{-2}$	586.1	2.06
	400	100.60	279.7	$3.8 \cdot 10^{-2}$	586.9	2.06

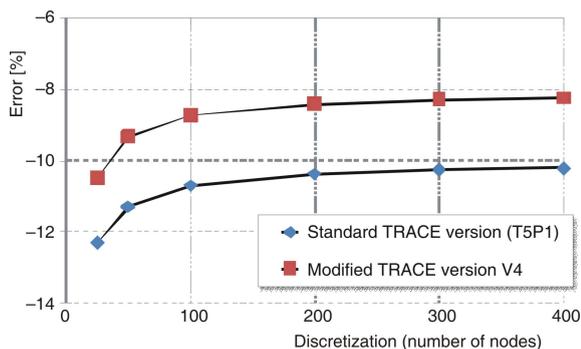


Figure 12. Comparison of error for different discretization for both TRACE versions

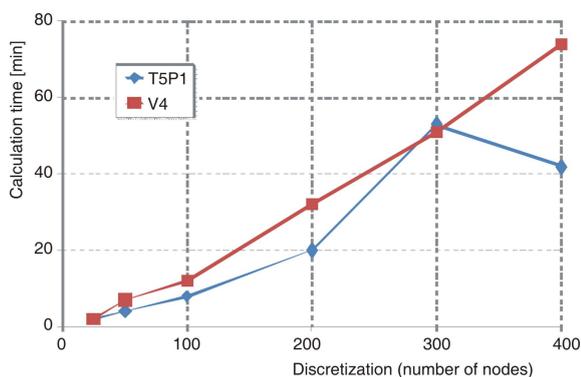


Figure 13. Comparison of calculating time for different discretization

tively. The error of the power calculations is between -12.3% and -10.2% for the different discretization of the standard TRACE code and between -10.5% and -8.2% for the modified TRACE code. Figure 12 shows the results of the error calculation.

The reason for the underestimation of outlet temperature, temperature difference and power is the use of empirical correlations for flow regime models with an error of up to 20% (Kataoka and Ishii) in TRACE for the secondary side (Water/Steam) [2, 12].

However, the TRACE version with standard Nusselt number reaches the worst results with an approximate error value of -10% but the best results are reached by TRACE version with the implemented Nusselt number V4 with an approximate value of -8% . The differences of the error calculation of 300 nodes compared to 400 nodes is for both TRACE versions -0.05% . Considering the calculating time, which rises with a finer discretization (fig. 13), an adequate choice taking into account both aspects is found for 300 nodes.

SUMMARY AND OUTLOOK

TRACE is an efficient tool for thermal-hydraulic calculations. This study shows that it can also be used

for modeling helical coil steam generators for high temperature gas-cooled reactors and gives an estimation of an accurate discretization. The standard Nusselt number of TRACE does not reach as good results as the modified Nusselt number for helical tubes.

An optimum for the discretization and the calculation time is found for 300 nodes.

The next step is to modify the TRACE model to investigate the temperature profile under transient conditions. The results of TRACE can be used for a stress analysis in which fatigue and lifetime have to be analyzed.

AUTHOR CONTRIBUTIONS

Theoretical analysis was carried out by M. Esch. The manuscript was written by M. Esch, D. Knoche, and A. Hurtado. Figures 1-3 have been previously published in several publications by the former Hochttemperatur-Reaktorbau GmbH (HRB), where by Westinghouse Electric Germany GmbH is the legal successor of HRB. These figures have been modified and adapted by M. Esch. All other figures were prepared and created just by M. Esch.

Nomenclature

D	– diameter of tube cylinder
d	– diameter of tube
Exp.	– experimental
f_a	– flow factor
l	– tube length
Nu	– Nusselt number
No.	– number of tube cylinder
P	– power
Pr	– Prandtl number
Re	– Reynolds number
s_L	– longitudinal pitch
T	– temperature
t	– number of turns
x_L	– non-dimensional longitudinal pitch/ d
x_T	– non-dimensional transversal pitch/ d

Greek symbols

ε	– inclination angle
v	– normalized temperature

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**НУМЕРИЧКА ДИСКРЕТИЗАЦИОНА АНАЛИЗА МОДЕЛА НТР
ПАРОГЕНЕРАТОРА У ТЕРМОХИДРАУЛИЧКОМ ПРОГРАМУ TRACE**

За будуће пројекте високотемпературних реактора, за потребе производње електричне енергије или грејања, парогенератор је критична компонента. Уобичајено решење је парогенератор са хеличним намотајима који се састоји од неколико паралелно везаних цеви које формирају цилиндричне различитих пречника. Овакав тип парогенератора користи се код торијумских високотемпературних реактора. У овом раду, температурни профил анализиран је применом нодалног термохидрауличног кода TRACE за парогенератор торијумског високотемпературног реактора. Утицај нодалне анализе испитиван је у оквиру овог рада и поређен са експерименталним резултатима из прошлости. Резултати стандардног кода TRACE упоређени су са резултатима добијеним модификованим Нуселтовим бројем за примарну страну. Примењена корелација за пренос топлоте развијена је у оквиру ранијег немачког НТР програма. Овај рад показује да су обе верзије кода TRACE стабилне и да омогућавају разматрање захтева који се постављају при примени нодова.

Кључне речи: нумеричка анализа стабилности, TRACE, парогенератор