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Selected design and construction aspects of supercritical steam generators for high temperature reactors

Article presents design and construction considerations on supercritical (once-through) steam generator using high and very high temperature reactor cores as heat source. Helical-coil steam generators are preferred over other types of design thanks to their increased heat transfer rate and compactness. Applicable modernised Rankine cycle and changes in thermophysical parameters of water in the neighbourhood of critical and pseudocritical points are examined. Correlations determining heat transfer coefficient are analysed in order to select the most applicable among them. Critical design aspects of such a supercritical nuclear steam supply system are discussed.

1 Introduction

Because of low overall efficiency of thermodynamic cycles of conventional (with pressurized and boiling water reactor units) nuclear power plants, which leads to ineffective use of nuclear fuel, focus should be laid on alternative technologies such as high temperature reactor (HTR) and very high temperature reactors (VHTR). The coolant temperature at output of their cores is much higher than in the case of pressurized water reactor units, widely used in stationary power engineering. This allows steam generation system to produce steam with much higher parameters, what obviously affects cycle efficiency.

Live steam parameters are limited by available construction materials. It can be safely assumed that parameters as high as 28MPa/550 °C/580 °C are available from technological point of view. This means that both, steam pressure and temperature, are higher than critical for water. Diagnostics of advanced power conversion systems such as this will need a set of relationships between main construction as well as operation parameters.

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2 Supercritical Rankine cycle application considerations

Calculations of appropriate thermodynamic cycle provide information about required parameters of the working medium in characteristic points of installation, for example temperature and pressure of working medium at the inlet of the steam generator and temperatures and pressures at inlet and outlet of the reheater section. When data about the needed power (amount and type) is supplied as a project input, calculations of thermodynamic cycle provide output in form of thermal power needed to be generated in reactor core and supplied to steam generator.

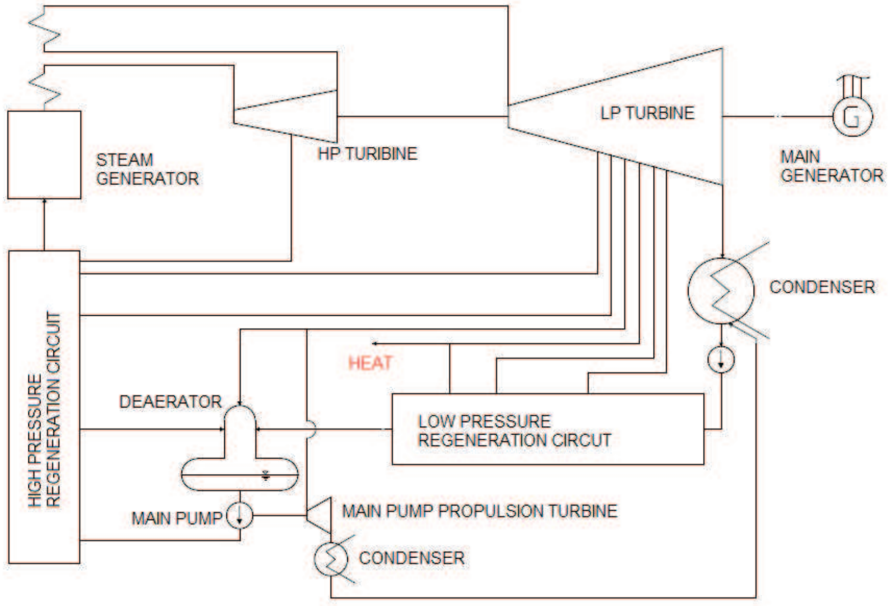

Figure 1. Power conversion system.

3 Heat-flow calculations of a helical-coil heat exchanger

One of the main problems that have to be solved to fully use the potential of HTR and VHTR units in stationary energetics is construction of optimal heat exchanger (steam generator) characterized by relatively small size and weight at reasonable cost. This can be achieved by implementing heat exchange surface in form of concentric, multi-turn spirals. This type of heat exchanger is preferred due to an increased heat transfer what obviously leads to reduction of size and cost.

The pressure loss of helium coolant is one of the most important design factors. It determines the power needed to drive the main circulator (feeding helium into the reactor core through steam generator and piping). This power rises very fast with increasing velocity of helium. It is then very important to find its optimum value, where we can benefit from increased, due to higher velocity, heat transfer coefficient and do not suffer from unreasonable main circulator power levels. In the systems, where a fact of limited space has a significant influence on design process and economics, it could be acceptable to use higher (than optimal from economics point of view) speed to reduce the size of power conversion system main components.

Steam generator proposed in this article produces a steam with supercritical parameters. This means that phase change does not occur and the water flowing inside steam generator tubes should be always considered as one phase flow (liquid or gas like). Heat exchange surface of such a steam generator should consist of high pressure bundle producing live steam with supercritical parameters from feed water and reheater bundle.

Calculations of a surface shaped in form of helical coils can be performed treating flow outside tubing as in a case of inline tubes arrangement (Fig. 2).

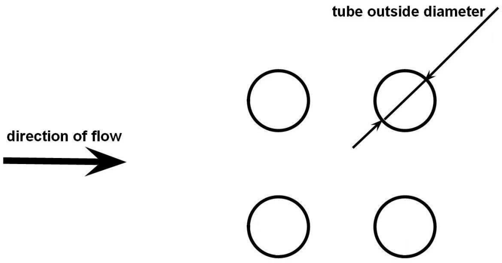

Figure 2. Inline tube arrangement.

This is an example of safe side assumption, as every extra turbulence caused by sloped tubing aids heat transfer and can be easily included in helium pressure loss calculations using empiric formulas.

Since steam flowing inside steam generator tubes is exhibited to a centrifugal force, the Jeschke correction should be applied:

$$\begin{aligned} \alpha &= \varepsilon\alpha' \ , \\ \varepsilon &= 1 + 1.77\frac{d}{R} \ , \end{aligned} \tag{1}$$

where α, α' is the heat transfer coefficient with applied Jeschke correction, heat transfer coefficient as calculated from Oka-Koshizuka or Colburn correlation, respectively, ε is the Jeschke correction factor, and d is the tube diameter and R is its bending radius.

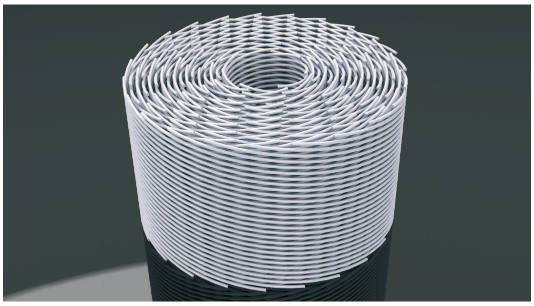

Figure 3. Simplified reheater model.

Reheater (Fig. 3) is essentially a gas-gas heat exchanger with steam flowing inside tubing and hot helium outside them. Known Colburn equation (for heat transfer to inline tubes) can be used to determine the heat transfer process from helium to pipe surface:

$$\mathrm{Nu} = 0.26\mathrm{Re}^{0.6}\mathrm{Pr}^{\frac{1}{3}} \;, \tag{2}$$

where Nu, Re and Pr are the Nusselt, Reynolds and Prandtl number, respectively. Determination of heat transfer coefficient at the internal side of the tubes can be with by done Colburn equation for flow inside tubes:

$$\alpha' = 0.023\frac{\lambda}{d}\mathrm{Re}^{0.8}\mathrm{Pr}^{0.4} \;, \tag{3}$$

where λ is the thermal conductivity.

Numerical and experimental investigations, performed from late 50s by many researchers, on a heat transfer to supercritical fluids (e.g. water above critical point) resulted in empirical correlations that can be used to determine heat transfer coefficients inside high pressure bundle (Fig. 4). These equations can be roughly categorized into two groups. First can be described as Dittus-Boelter equations derivatives, characterized by similar form and ease of use. Second are complicated equation sets based on mechanistic studies (e.g. Kurganov equations). While the first group may be used to estimate heat transfer process to supercritical fluid at normal state, they fail to stay accurate where the deteriorated and enhanced heat transfer phenomena occurs, with the second group of

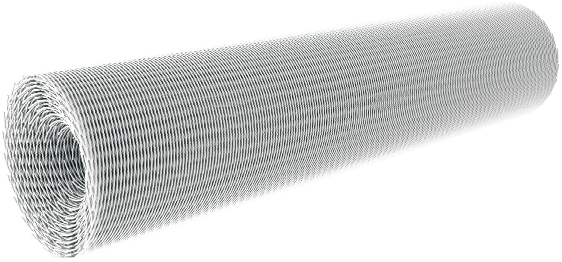

Figure 4. Supercritical pressure bundle model.

equations are in most cases to complicated for a engineering use (being forced out by computational fluid dynamics techniques).

One of possible solution to equation selection problem is correlation of Oka-Koshizuka [3]:

$$\begin{aligned} &\mathrm{Nu} = 0.015\mathrm{Re}^{0.85}\mathrm{Pr}^{0.69-\frac{81000}{\dot{q}_s}+f_c\cdot\dot{q}} \,, \\ &\dot{q}_s = 200\cdot G^{1.2} \,, \end{aligned} \tag{4}$$

where G is the mass velocity, and $\dot{q}$, $\dot{q}_s$ is the heat flux and critical heat flux, respectively.
Correction factor, taking into account the influence of heat flux, can be calculated in three ranges depending on value of specific enthalpy from equation:

$$f_c = \begin{cases} 2.9\times10^{-8}+\frac{0.11}{\dot{q}_s}, & i < 1.5\left[\frac{\mathrm{MJ}}{\mathrm{kg}}\right] \\ -8.7\times10^{-8}-\frac{0.65}{\dot{q}_s}, & 1.5\left[\frac{\mathrm{MJ}}{\mathrm{kg}}\right] \le i \le 3.3\left[\frac{\mathrm{MJ}}{\mathrm{kg}}\right] \\ -9.7\times10^{-7}-\frac{1.30}{\dot{q}_s}, & 3.3\left[\frac{\mathrm{MJ}}{\mathrm{kg}}\right] \le i \le 4.0\left[\frac{\mathrm{MJ}}{\mathrm{kg}}\right] \end{cases} \tag{5}$$

where i is bulk fluid specific enthalpy. This equation while preserving simple, Dittus-Boelter like form, can predict the heat transfer coefficient deterioration and enhancement. Heat transfer deterioration is a phenomenon similar to departure from nucleate boiling in sub critical region and occurs at high heat fluxes and relatively low mass velocities. Heat transfer enhancement occurs at low heat fluxes with relatively high mass velocities.

4 Construction considerations

Internal shield (Fig. 5) composed of reactor grade graphite or (better) high temperature insulation material, approved for nuclear installation use, is highly suggested. When installed protects the pressure vessel of heat exchanger from influence of high temperature (t_1), allowing the use of less expensive construction materials such as reactor pressure vessel steel SA-508 instead of expensive high temperature alloys such as IN617.

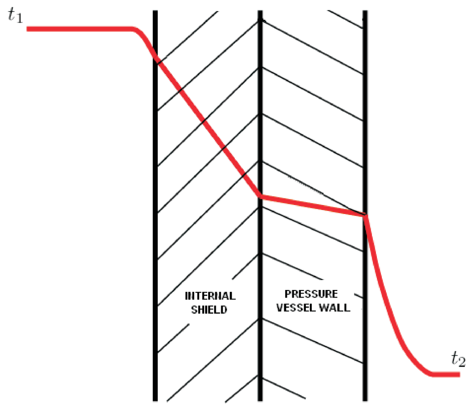

Figure 5. Internal shield.

Outer insulation is discouraged, because heat losses to exterior (at temperature t_2) have less significant impact on overall unit economics than pressure wall temperature, as this insulation neglects effects of internal shielding usage.

5 Results

Experience and data gathered during the design process, as well as relationships presented in article, provide a first step of understanding the operation of high power helical coil heat exchangers from the point of view of diagnostics. Performed heat-flow and the pressure vessel calculations were treated as an iterative process, giving the optimal form of the steam generator. Obtained size and form of the heat exchange surface determined the external dimensions of the construction, which proved to be several times smaller than conventional fuel-fired boilers producing supercritical steam parameters operating on comparable power levels (Fig. 6 on the right).

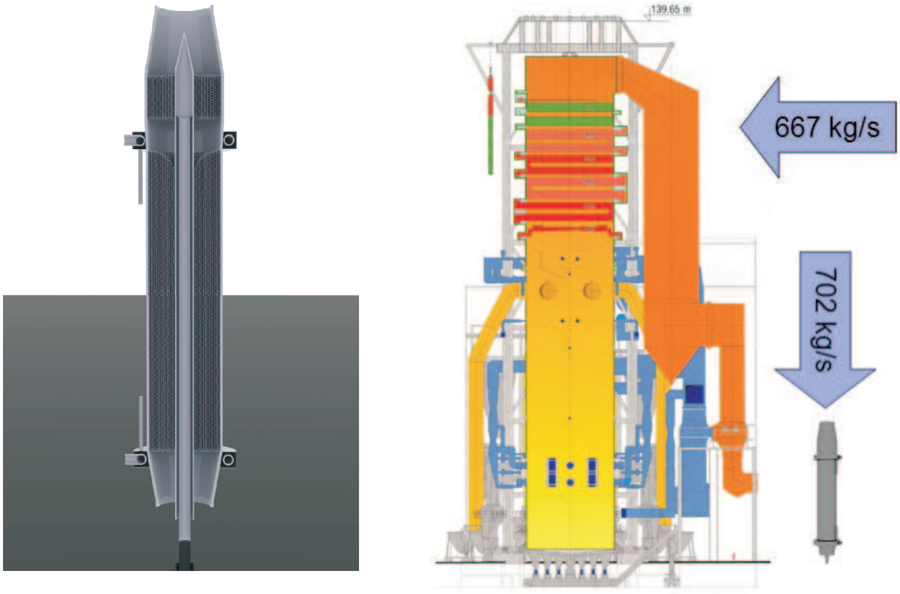

Figure 6. Supercritical steam generator model.

Comparison of the obtained heat exchange surface to that installed in the THTR-300 (thorium high temperature reactor) power plant steam generators results in less than twice smaller ratio of surface area to net power. Thanks to the high pressure of helium it was possible to reduce its speed dramatically reducing power needed to drive the main circulator.

Figure 6 (left side) represents model of designed steam generator, utilizing heat from 3 GT-MHR (gas turbine modular helium reactor) units to produce 853.8 MWe (overall power conversion efficiency 47.44%). Unit is 32.77 m high, having average diameter of 5.55 m. Central column that can be seen in the axis of steam generator serves as supply of secondary steam to the reheater and as a reheated steam outlet. Reheater bundle has 17 layers composed of 267 tubes: 57 mm diameter, 14.9 m long. The high pressure bundle has 18 layers composed of 279 tubes 50 mm diameter, 142.0 m long.

One of the goals of optimization process is to design layers with possibly equal height. This goal was achieved in design of reheater bundle. As for the high pressure bundle the difference between height of the first and last layer is 1.26 m. Being that the height of the whole bundle is 22.78 m it is acceptable.

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Wybrane zagadnienia konstrukcji i projektowania wytwornic pary o parametrach nadkrytycznych współpracujących z reaktorami wysokotemperaturowymi

Streszczenie

Omówiono wybrane zagadnienia konstrukcji i projektowania przepływowych wytwornic pary współpracujących z rektorami wysoko i bardzo wysoko temperaturowymi. Wytwornice pary o powierzchni wymiany ciepła w formie koncentrycznych spiral wielozwojowych są preferowanym typem dzięki intensyfikacji wymiany ciepła, której towarzyszy redukcja wymiarów zewnętrznych. Przedstawiony został stosowny obieg Rankine'a oraz przeanalizowane zmiany parametrów termofizycznych wody w otoczeniu punktu krytycznego i pseudokrytycznych. Artykuł zawiera analizę i uzasadnienie doboru korelacji określających intensywność procesu przejmowania ciepła przez wodę w stanie nadkrytycznym oraz stosowne poprawki umożliwiające stosowanie jej w przypadku omawianego typu konstrukcyjnego wytwornicy pary.