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Conceptual design of a bayonet tube steam generator with heat transfer enhancement using a helical coiled downcomer

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ABSTRACT

Bayonet tube heat exchangers are a proposed solution for advanced nuclear reactor steam generators and heat removal systems, in particular in liquid metal cooled reactors. However, the performance of this heat exchangers is not very high due to the limited heat transfer surface; thus, many long bayonet heat exchangers are needed to remove significant power values. In the present paper, the use of a helical coiled downcomer inside the bayonet is proposed, instead of the traditional straight one, as a passive heat transfer enhancement method. The helical coiled downcomer acts on the annulus as a swirl flow device; for the evaluation of heat transfer and pressure drop it can be considered as a helical coiled wire or a helical coiled tape. The global thermal resistance between the heat source (external flow of primary fluid) and the heat sink (secondary fluid) is reduced, while the pressure drop is not excessively increased. The component behavior has been simulated using the thermal-hydraulic code RELAP5-3D, with lead and water respectively as primary and secondary coolants. A one-dimensional model has been adopted, modifying the heat transfer coefficient and the frictional pressure losses to properly simulate the helical coil effect with two different methods: the use of a heat transfer coefficient multiplication factor and the adoption of the swirl tube heat transfer mode. The component has been operated as a steam generator considering the parameters and the boundary conditions of ALFRED reactor proposed design. Two different downcomer tube dimensions have been considered (6–8 mm and 8–10 mm ID-OD) with five helical pitches (5, 7.5, 10, 15 and 20 cm), which have been selected taking into account the manufacturing constraints. The results show a significant improvement of the bayonet heat exchanger performance. The removed power increases more than 8% and the steam superheating increases around 23 K for the best configuration.

1. Introduction

1.1. Steam generator options for advanced reactor

Nuclear power is considered a very important energy source to reduce CO_2 emissions, air pollution and the dependency on fossil fuels. However, due to social opposition, particularly after the Fukushima accident, there is the need of a safer and a more sustainable development of civil nuclear energy. For this reason, both in industry and academia there is a strong effort towards the design of the so-called "Generation IV reactors" with a higher safety than the previous generations (Generation IV technical forum, 2014) and Small Modular Reactors (IAEA, 2016).

This new reactor generation is very different from the current one for both the adopted technologies and the plants design. One of the main components that is considerably different from current operating reactors is the steam generator (SG) (Ilyas and Aydogan, 2017). In the large majority of generation II and generation III plants U-tubes SGs have been adopted and they have shown a good heat transfer capability and reliability. Despite that, in the proposed designs for generation IV reactors and Small Modular Reactors they are no longer considered anymore in favor of once-through SGs. This type of SGs have two main advantages: the absence of the recirculation flowrate (in fact all the flowrate is vaporized in one stage) and the possibility to superheat the steam (leading to a higher plant efficiency and benefits for the turbines). The main drawback is the occurrence of the dryout in the evaporation process. However, since it is a temperature difference driven heat transfer the maximum wall temperature is limited and the risk of burn out is avoided even if the heat transfer is reduced.

Once-through SGs can be subdivided in different categories; the types mainly used or proposed for advanced nuclear plants are: straight tube SGs, helical coil SGs and bayonet tube SGs. Straight tube SGs are the most common ones, they have been adopted in some current operating reactors (in particular Babcock & Wilcox plants) and for generation IV ones, for example in the Sodium Fast Reactors BN-600 (Buksha et al., 1997) and BN-800 (Fadeev et al., 2016). Helical coil SGs

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Nomenclature

d	Tube diameter
D	Helical coil diameter
e	Wire coil diameter
f	Darcy friction factor
h	Wall to fluid heat transfer coefficient
k	Heat transfer coefficient multiplication factor
ID	Downcomer tube inner diameter
OD	Downcomer tube outer diameter
p	Helical pitch

Dimensionless parameter

De	Dean number
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number

Subscripts

a	Augmented Nusselt number/heat transfer coefficient
s	Smooth tube

are widely adopted in advanced reactors for their compactness and higher heat transfer capability. They were used for example in the Super-Phénix reactor (Verriere et al., 1984) and they are proposed for Small Modular Reactor such as IRIS (Cinotti et al., 2002) and SMART (Kim et al., 2013). Bayonet tube SGs were studied in the past for sodium cooled reactors, while now they are proposed for lead cooled reactors in particular. Bayonet tube SGs are extensively presented in the following section. Among the proposed Generation IV reactors, some designs do not have SGs or because gas is used as primary coolant or because supercritical water is adopted that is directly vaporized in the core. However, these reactors still present various types of heat exchangers to be used for in accidental cases.

1.2. Bayonet tube steam generators

A possible solution for the SGs and for safety dedicated heat exchangers (such as for decay heat removal) is the use of bayonet tube heat exchangers (Caramello et al., 2016). Bayonet heat exchangers are of new adoption in the nuclear sector and they are mainly proposed for pool-type liquid metal reactors (Damiani et al., 2013) and for some Small Modular Reactors (SMR) (IAEA, 2016).

In its simplest configuration, a bayonet heat exchanger is composed of two coaxial tubes, Fig. 1. The secondary fluid (e.g. water) enters into the heat exchanger from the upper part of the inner tube and flows downward in the downcomer receiving heat from the rising fluid in the annulus; so an internal heat transfer between the same fluid occurs. At the end of the downcomer the fluid inverts its motion inside the inversion chamber and then flows upward in the annular region between the inner tube and the outer tube. Flowing in the annular region, the secondary fluid removes heat from the primary fluid that downflows externally to the bayonet (e.g. liquid lead in Fig. 1); the external heat transfer is temperature controlled. The steam is then collected into a header and sent to the turbines. On the top of the liquid lead pool, the presence of an inert gas allows the thermal expansion of the liquid.

It is possible to find more complex layouts where the inner tube is split in two different tubes with an insulation layer between them. This is done to increase the thermal resistance between the downcomer and the annular region, thus reducing the internal heat transfer (to the fluid into the downcomer) that decreases the efficiency of the component during normal operation. Conversely, during accidental operation internal heat transfer can be useful to reduce the power removed from the primary fluid so to avoid the freezing of the liquid metal. Therefore, this configuration is preferable during normal operation to increase the outlet steam temperature but it can be disadvantageous in accidental conditions. A possible solution consists in a particular downcomer design that contains steam during normal operation and water in case of an accident. This allows the modification of the downcomer thermal resistance based on the operating condition (De Fur, 1975).

Another possibility is to double also the outer tube, placing a mixture of inert gas and metal powder inside the gap. The presence of the gas and powder mixture does not reduce too much the heat transfer between the primary and secondary fluid (even if the component's performance is decreased) but prevents the contact between the two fluids in case of a rupture. This may not be so dangerous in case of a lead-cooled reactor but it is very important if the primary fluid is sodium. The adoption of different bayonet layouts may also be very useful to control the cooling rate of the external fluid (heat source) to avoid possible freezing of the liquid metal, in particular during accidental transients (Caramello et al., 2017).

More recently Damiani and coworkers proposed an alternative steam generation system that uses bayonet heat exchangers with the coolant under vapor phase (Damiani et al., 2014; Damiani and Revetria, 2015). The system called External Boiling Bayonet Steam Generator (EBBSG) is a combination between bayonet tube heat exchangers and the Loeffer external boiling concept. The main advantage of this solution is a significant reduction of the secondary side pressure, thus enhancing the safety of the plant.

In general, once through bayonet SGs present several advantages: they are a relatively simple manufacturable component and, since they are fixed only in the upper side, thermal expansion stresses are not an issue. Moreover, their modularity allows the extraction and substitution in case of a rupture. Finally, having the inlet and outlet on the same side of the component reduces the piping immersed in the liquid metal pool. The main disadvantages are a limited heat transfer surface and the possibility of fouling deposition in particular in the bayonet inversion chamber.

The adoption of bayonet heat exchanger for liquid metal reactors is undergoing experimental assessment in various facilities. Italy is very active in this sector with two series of experimental campaigns devoted

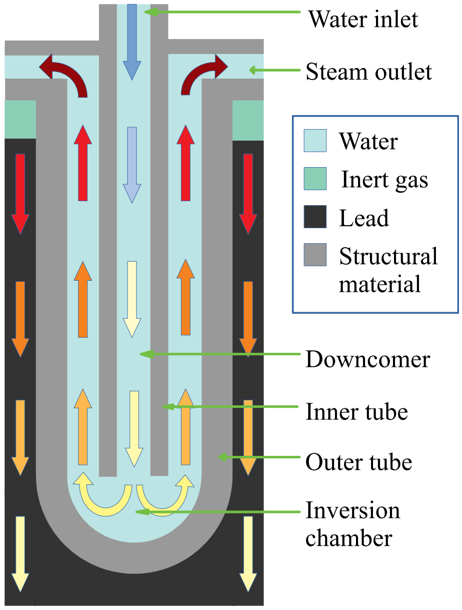

Fig. 1. Simplified scheme of a bayonet heat exchanger with liquid lead as primary fluid.