Thermal hydraulic analysis of Alfred bayonet tube steam generator

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Thermal hydraulic analysis of Alfred bayonet tube steam generator

M. Caramello[a], M. Gregorini[b], M. De Salve[a], C. Bertani[a], A. Alemberti[b] , B. Panella[a]
[a]*Department of Energy, Politecnico di Torino, Corso Duca degli Abruzzi, 24, 10129 Torino, Italy*
[b]*Ansaldo Nucleare S.p.A., Corso F. M. Perrone 25, 16161, Genova, Italy*

Abstract – *The paper analyzes the performance of ALFRED steam generator from the thermal-hydraulic point of view highlighting the effect of some design features. The parameters object of the study are the regenerative heat transfer, the dimension of the inner tube and the length of the bayonet. The system code RELAP5-3D/2.4.2 has been chosen for the analysis. Sensitivities analysis allowed the determination of the different design parameters influence, here briefly summarized. The increase of regenerative heat transfer affects the efficiency of the steam generator through a degradation of the outlet steam quality: the number of bayonet tubes required to remove the nominal power increases with the increase of the global heat transfer coefficient of the inner tube. A higher inner diameter results in a larger surface area for the regenerative heat transfer and in a higher heat transfer coefficient in the annular region because of the reduction of the cross section. The result is an improvement of the performances of the steam generator thanks to the dimension reduction of the annular gap. Finally, if the height of the bayonet tube is reduced by 1 meter, the number of bayonet tubes required to remove the nominal power increases up to 20%.*

I. INTRODUCTION

In the framework of Generation IV nuclear reactors there is a particular interest in the development of lead cooled fast reactors[1]. Liquid metal reactors are often characterized by a pool-type primary system which contains almost all the primary components. This layout requires to review the design of some components of the primary system, such as the steam generator (SG).

Steam generators for evolutionary reactors are characterized by nonconventional geometries: one of the design requirements is to produce high superheated steam to guarantee a high thermodynamic cycle efficiency and therefore satisfy one of the generation IV goals[2].

One of the possible steam generator for liquid metal reactors is the bayonet configuration. The simplest bayonet element is constituted by two coaxial pipes. Usually, the inner fluid flows from the top to the bottom of the steam generator inside the inner tube, then, it is directed in the annular gap formed between the pipes. The coolant outside the bayonet flows in countercurrent flow with respect to the fluid in the annular riser.

Among the features of the bayonet type SG there is the regenerative heat transfer. Thanks to the regenerative heat transfer the fluid in the annular riser pre-heats the fluid flowing in the inner tube. This effect must be carefully taken into account since an excessive regeneration on the top of the bayonet may imply a degradation of the steam quality because of the steam cooling and local condensation.

At a fixed height of the steam generator the inner wall of the annular region is always at a lower temperature than that of the fluid inside the annulus because the direction of thermal power is from the outside to the inside of the bayonet. A first effect of this temperature distribution is the asymmetric boiling: the fluid in the annulus evaporates only on the external surface which temperature is higher than the saturation value. This configuration causes a loss of power towards the fluid in the inner tube of the bayonet: in the boiling region, for example, steam bubbles which go near the inner wall may condense. In the superheated region, the steam near the inner wall is cooled and local condensation may occur nearby the end of the boiling region, where the steam is still saturated.

These considerations show the need to use thermal insulating techniques to reduce the heat transfer between the inner tube and the annular gap if high quality steam is required.

The first studies on the bayonet heat exchanger took places in the seventies. Dickey and Bendixsen[3] proposed a mathematical model to describe the heat transfer between a horizontal bayonet bundle and a fluidized bed of radioactive liquid wastes. Their results show that the power removed by the bayonets increases when the regenerative heat transfer inside the bayonet is prevented. The first studies had the aim to characterize bayonet steam

generators to be used in the first sodium fast reactors because, thanks to the possibility to create double-walled bayonets[4], the configuration is particularly suitable to reduce the probability of interaction between sodium and water, and detect in real time the yielding of a first physical barrier[5].

Recently, the bayonet tube steam generator has been chosen for ALFRED (Advanced Lead Cooled Fast Reactor European Demonstrator) reactor[6] and Damiani et al.[7] presented the conceptual design for the bayonet element and for the whole steam generator by describing how the dimensions of the tubes, the length of the bayonets and the material were chosen.

The present paper studies the thermal-hydraulic performance of the ALFRED steam generator in the light of some of its characteristic parameters. The analysis has been carried out creating a representative model of the steam generator by means of RELAP5-3D/2.4.2, which is a commercial thermal hydraulic system code able to analyze accidental transients in nuclear power plants[8]. The code is based on a nonhomogeneous and nonequilibrium model for the two-phase system that is solved in a fast, partially implicit numerical scheme to perform economical calculation of system transients[8].

The objective of the analysis is to quantify the effects of some features of the system, namely the length of the bayonet, the diameter of the inner tube and the regenerative heat transfer, on the steam generator performance. The parametrical analysis has been performed by considering different lengths of the bayonet (5 m and 6 m) and varying the dimension of the inner tube and the thermal conductivity of the insulator between the fluids in the inner tube and annular gap.

II. BAYONET REFERENCE GEOMETRY

Figure 1 shows a cutaway of ALFRED bayonet tube. The bayonet is designed to add an additional physical barrier between water and lead and therefore reduces the possibility of their interaction in case of pipe failure, as well as to detect, in real time, the failure of one of the two pipes of the external wall.

The external wall consists of three layers. A porous medium formed by high conductivity powders and helium at the pressure of 4 bar is interposed between two metallic layers made of T91 stainless steel. The measurement of the helium internal pressure allows the detection of any rupture of one of the two walls: since the helium design pressure is intermediate between those of lead and water, the monitoring system is potentially able to recognize the location of the rupture. Also the internal wall consists of three layers. High insulating paint (thermal conductivity of 0.6 W/m/K in the base case) is interposed between the metallic layers made of T91 to reduce the global transmittance and therefore to prevent the regenerative heat transfer. The reference steam generator data are reported in table I, while the bayonet tube geometrical data are reported in figure 2[7].

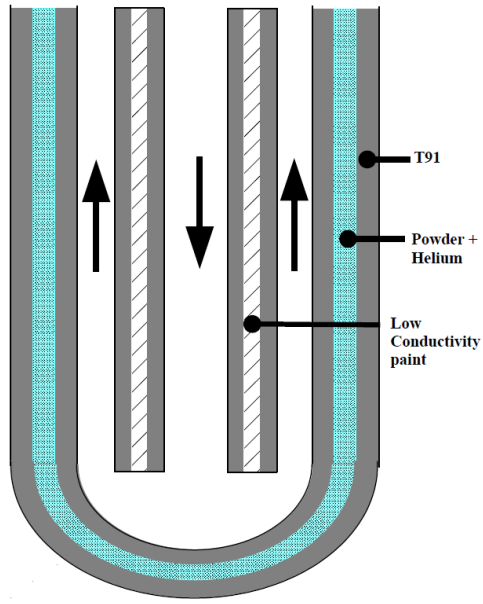

Fig. 1. ALFRED bayonet tube section.

TABLE I

Steam generator data

Parameter	Value	Unit measure
Thermal power per SG	37.5	MW
Number of SG	8	
Number of bayonets per SG	510	
Pitch/diameter ratio	1.42	
Water pressure	18	Mpa
Feedwater temperature	335	°C
Steam outlet temperature	450	°C
Lead inlet temperature	480	°C
Lead outlet temperature	400	°C
Water flow rate	24.068	kg/s
Lead flow rate	3247.54	kg/s

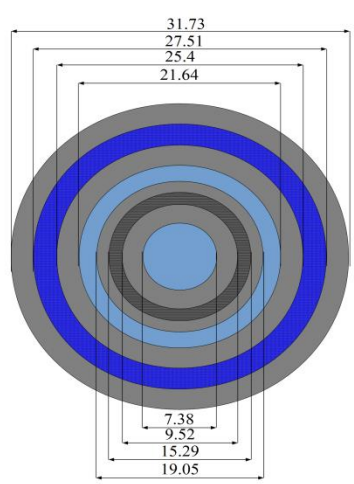

Fig. 2. ALFRED bayonet tube geometry [mm].

III. THE NUMERICAL MODEL

Figure 3 shows the sketch of the RELAP5-3D model. The ALFRED steam generator is simulated by means of a single bayonet tube, that is representative of the whole bundle of bayonets.

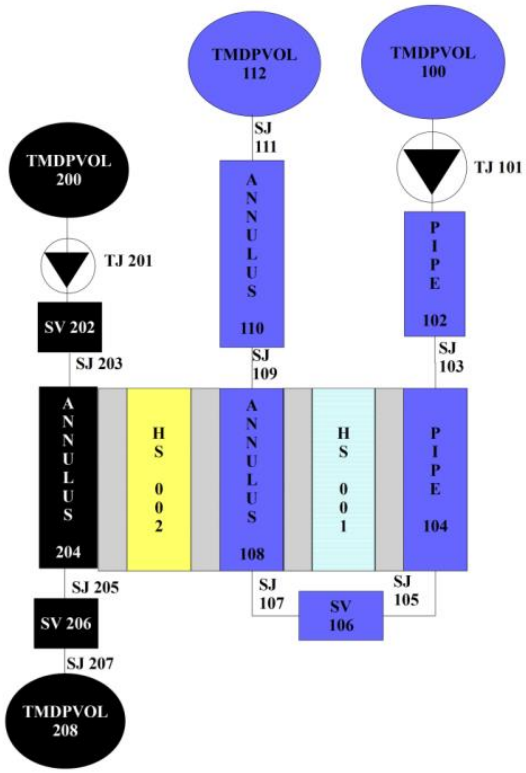

Fig. 3. RELAP5-3D model of ALFRED steam generator.

The partial differential equations governing the fluid-dynamics and heat conduction in heat structures are solved with a semi-implicit advancement scheme with time step control, same time step for heat conduction and hydrodynamics and implicit advancement of the heat conduction/transfer with the hydrodynamics.

The water control volume is simulated with a pipe element (PIPE 104), that is representative of the descending tubes, and with an annulus component (ANNULUS 108) representative of the annular gaps. A single volume component (SV 106) is interposed between the pipe and the annulus to simulate the inversion region. Single junctions 105 and 107 are defined to take into account localized pressure losses due to flow reversal. Two additional control volumes (PIPE 102 and ANNULUS 110) are linked to the bayonet tube to monitor the characteristic parameters of the fluid at the inlet and at the outlet of the active region. The flow rate is fixed to the nominal value by a time dependent junction (TJ 101), while the pressure outlet boundary condition is set by a time dependent volume (TMDPVOL 112).

The lead control volume is simulated considering an equivalent channel (ANNULUS 204). Its area is defined so as to obtain the design lead velocity and the frictional pressure losses on the external side of the bundle. The annulus is connected to two single volumes (SV 202, SV 206) that allow the flow rate at the inlet and at the outlet of the steam generator to be monitored. Nominal flow rate is fixed by a time dependent junction (TJ 201), while the pressure outlet boundary condition at the bottom of the steam generator is set by a time dependent volume (TMDPVOL 208).

The inner pipe of the bayonet that thermally connects the fluid downflowing in the inner tube and the fluid rising in the annular region is simulated with a cylindrical heat structure (HS 1001). The heat structure is made of three layers: the first and the third regions simulate the metallic layers of the pipe (T91) in terms of heat capacity and thermal conductivity; the second layer simulates the insulating paint which prevents the regenerative heat transfer.

The external pipe allows the heat transfer between the water flowing in the annular gap and the lead. It is simulated as a cylindrical heat structure (HS 1002) made of five layers. The first layer takes into account the possible presence of fouling inside the pipe: it is simulated with a 50 μm layer with a thermal conductivity of 2 W/m/K. The second and forth layers simulate the metallic parts of the pipe (T91), the third layer simulates the gap containing helium and the high conductivity powder, and the outermost layer simulates a tantalium coating with a thermal conductivity of 50 W/m/K.

As far as the heat transfer coefficients are concerned, the correlation adopted for liquid lead is the one from Kazimi and Carelli suggested for heat transfer in pipe bundles with and without crossflow[9]. The water inside the bayonet is characterized by several heat transfer modes such as single phase heat transfer, boiling and condensation. For the single phase heat transfer the classical Dittus-Boelter correlation has been adopted, whereas the Chen heat transfer correlation is used in subcooled and saturated boiling. The heat transfer coefficient that has been adopted during condensation in the annular region of the bayonet is calculated as the maximum between Shah and Nusselt correlations. A detailed description of these models can be found in References[9].

IV. RESULTS AND DISCUSSION

The effects of the conductivity of the insulator inside the inner tube and the effects of the inner tube diameter are evaluated on both 5m-long bayonet tube and 6m-long bayonet tube.

In order to have a general idea of the temperature distribution inside the steam generator, figure 4 shows the temperature profile in water (blue line) and in lead (red line) along the reference bayonet tube (total length of 6 meters, insulator conductivity of 0.6 W/m/K). The origin of the reference system is set at the bottom of the bayonet tube.

The component is characterized by a non-boiling region which takes the total length of the inner tube and a small region of the annular riser, a 2.5 m long boiling region and a 3 m long superheated region.

The region of the inner tube, where the regenerative heat transfer is the highest, is interfaced with the superheated steam in the annulus because it is the region where the temperature difference is the highest.

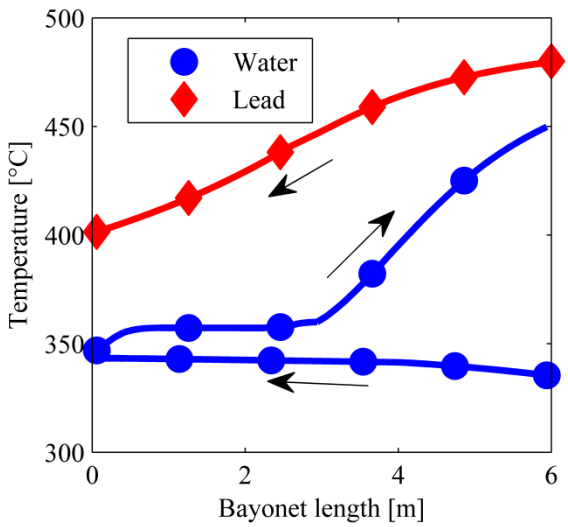

Fig. 4. Temperature profile in the SG.

IV.A. Insulation conductivity effect

The global heat transfer coefficient between the fluid in the inner tube and the fluid in the annular region is constrained by the high thermal resistance of the insulating paint that is placed between the two metallic layers. For this reason this parameter is the key for the regenerative heat transfer.

The contribution of the regenerative heat transfer is not constant along the bayonet as it depends on the temperature difference between the fluid in the inner tube and the fluid in the annular gap and on the heat transfer mechanism that is different for the single phase and for the two-phase region. The regions of the bayonet where the maximum power is transferred to the fluid in the inner tube are shown in figure 5 where the cumulated regenerative power fraction along the bayonet can be seen: 80% of the regenerative power is deposited in the region that is in thermal contact with the superheated steam, whereas the remaining 20% of power is due to the two-phase region and to the liquid single phase region; therefore, the main part of regenerative heat transfer takes place in the upper part of the bayonet and depends mainly on the temperature difference between the water in the inner tube and the water in the annular gap.

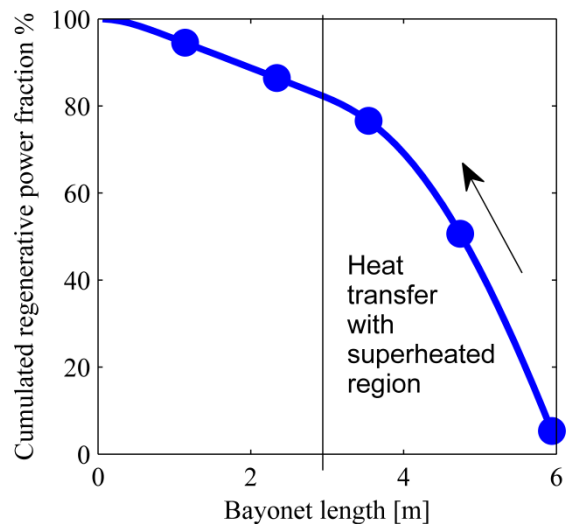

Fig. 5. Regenerative heat transfer distribution (reference bayonet case).

The effect of the insulator thermal conductivity on the temperature distribution is shown in figure 6, which represents the temperature in the inversion region at the bottom of the bayonet tube versus the insulating paint thermal conductivity for the 5 m bayonet (red line) and for the bayonet of 6 meters (blue line). As the thermal conductivity of the paint increases the fraction of power removed by the bayonet and absorbed by the fluid in the inner tube increases, with a consequent increase of the water temperature in the inversion region.

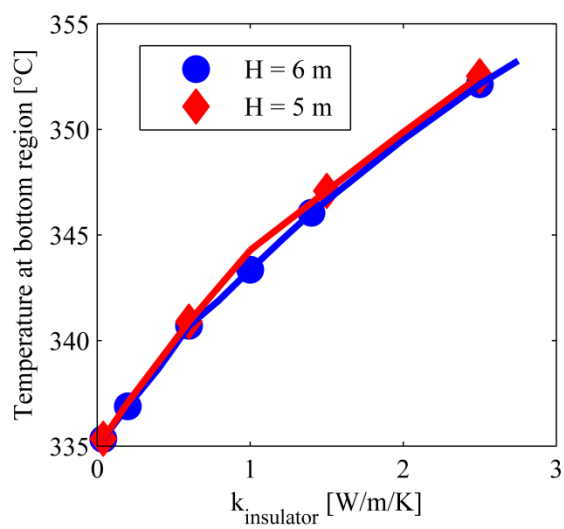

Fig. 6. Water temperature in the inversion region.

In order to study the effect of regenerative heat transfer the following procedure has been adopted. The thermal conductivity of the insulating paint has been varied from the minimum of 10^{-6} W/m/K to the maximum of 3 W/m/K, keeping the same length and the same radial stratigraphy of the reference bayonet tube. Ten equidistant values of thermal conductivity have been simulated for each bayonet length: less marks are reported in the plots for a better clarity.

For each value of thermal conductivity, the number of bayonet tubes that are necessary to remove the nominal power of the reactor has been predicted. The process has been applied to 5 m and 6 m long bayonet elements.

Also the thickness of the insulating paint may be modified to change the thermal resistance of the insulating layer; however, a change in thickness would result in a change of the diameters, thicknesses of the other layers and therefore of the flow area for the fluids: in order to avoid these effects, the possibility to change the insulating paint thickness has been discarded.

The regenerative heat transfer inside the bayonet tube produces a general deterioration of the steam generator performance.

Figure 7 shows the effect of the insulator thermal conductivity on the regenerative heat transfer (expressed as a percentage of the total power that is exchanged between the lead and the water). An increase of the insulator thermal conductivity up to 3 W/m/K causes an almost linear increase of the regenerative heat transfer up to about 10% of the total power.

Going from the case of perfect insulation to the one of poor insulation (thermal conductivity of 3 W/m/K), the number of bayonet tubes, that are required to remove the nominal power, increases of approximately 30% (figure 8) and the power removed by each bayonet tube decreases (figure 9).

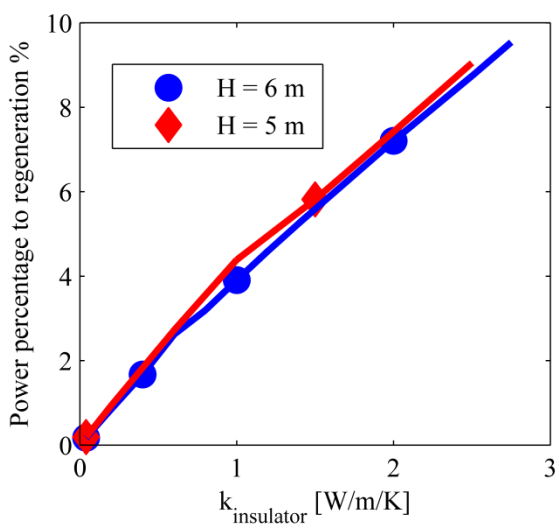

Fig. 7. Regenerative heat transfer.

This is generally true both for the reference 6 meters bayonet tube and the 5 meters one. The number of elements required to remove the same power increases by 25% reducing the length of the bayonet tube of 1 meter at a fixed insulation conductivity. This increase is due to two contributions. Firstly, the surface area of the 5 meters bayonet tube is 17% less than the 6 meters one, and secondly, the average heat flux for the 5 meters bayonet tube is about 5% less than the reference case, as shown in figure 10.

The average heat flux, shown in figure 10, is the ratio between the power removed by the single bayonet tube and its external surface area.

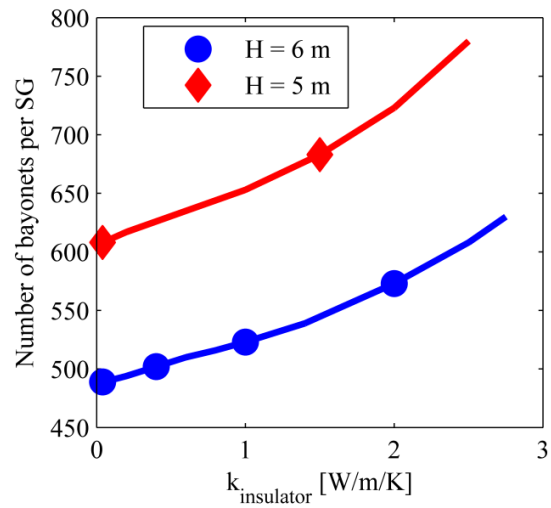

Fig. 8. Number of bayonet tubes per steam generator.

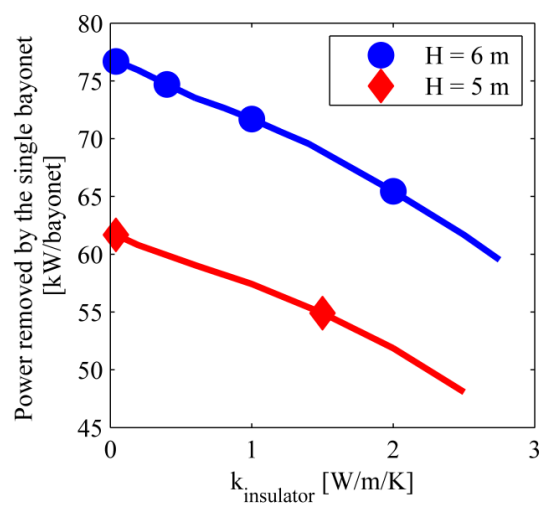

Fig. 9. Power removed by the single bayonet tube.

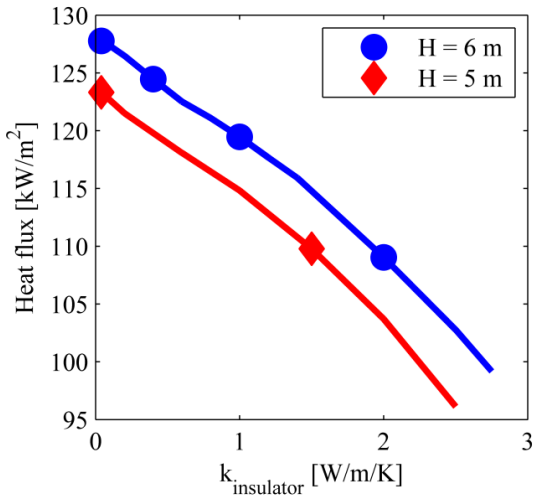

Fig. 10. Average heat flux.

IV.B. Inner diameter effect

To analyze the effect of the size of the inner tube on the performance of the steam generator, the inner diameter of the internal tube has been varied from 4 mm to 8 mm, being 7.38 mm the nominal value.

Five equidistant values of inner diameter have been simulated for each bayonet length: less marks are reported in the plots for a better clarity.

For each configuration, the number of bayonet tubes to be set in parallel to remove the nominal power has been evaluated for both 6 m-long and 5m-long tubes. The thickness of the layers of the internal tube have been kept constant, although, generally speaking, this would not be correct from a mechanical point of view, since the thickness of a tube depends on its diameter; however, since this preliminary work is merely focused on the thermalhydraulic performances, the mechanical issues have not been taken into account. As far as the outer tube is concerned, the values of diameter and thickness have been kept constant in order to analyze the results considering the same area of heat exchange with the lead for each bayonet tube. The increase of the inner diameter of the bayonet, under the hypothesis previously described, implies an increase of the cross section for the fluid inside the inner tube, a decrease of the cross section for the fluid flowing in the annular gap and an increase in the surface area devoted to the regenerative heat transfer.

As the internal diameter of the inner tube increases, the performance of the steam generator is enhanced. In fact the number of bayonet tubes that are required to remove the nominal power decreases of about 25% for the 6 meters bayonet tube and 35% for the 5 meters one (figure 11).

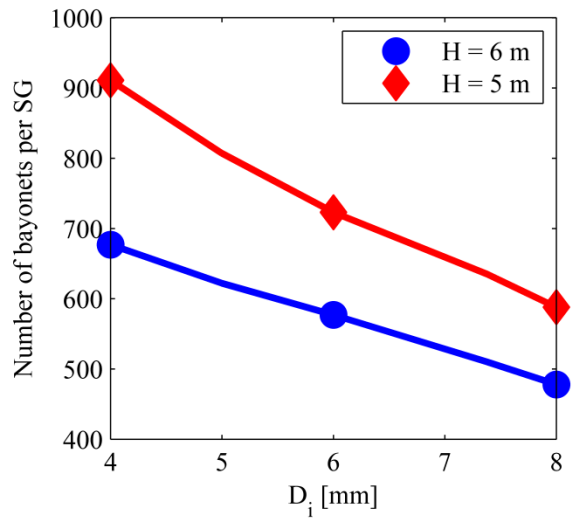

Fig. 11. Bayonet tubes per steam generator.

This improvement is reflected on the increased amount of power removed by each bayonet (figure 12) and on the efficiency of the heat transfer, expressed in terms of average heat flux (figure 13) as shown in figure 10. The 5 meters bayonet configuration has a larger number of bayonet tubes than the 6 meters solution, between 25% and 35%.

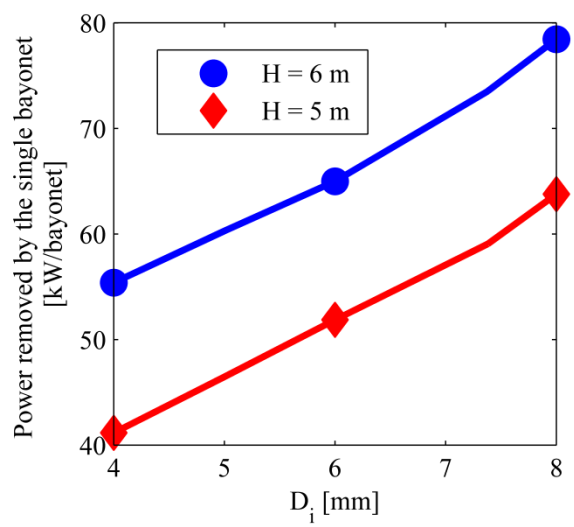

Fig. 12. Thermal power per bayonet tube.

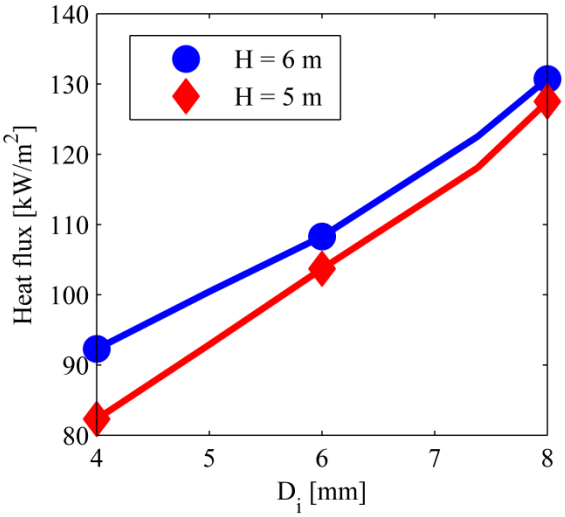

Fig. 13. Average heat flux.

The enhancement of the steam generator performance is mainly due to the increase of the heat transfer coefficient in the annular gap thanks to the decrease of its cross section. On the other hand, this reduction causes an increase of pressure drops along the annular riser (figure 14).

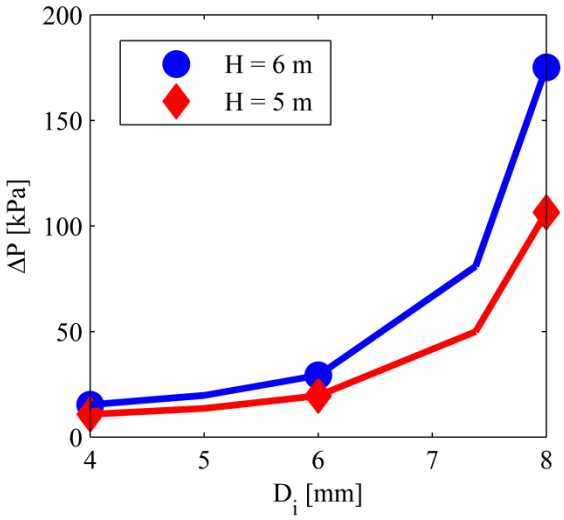

Fig. 14. Annular gap pressure losses.

The regenerative heat transfer rate is weakly influenced by the variation of the inner diameter: in the cases considered in this analysis the fraction of power received by the fluid in the inner tube is of the order of the 2.8% and the temperature at the bottom of the bayonet is nearly constant (figures 15 and 16).

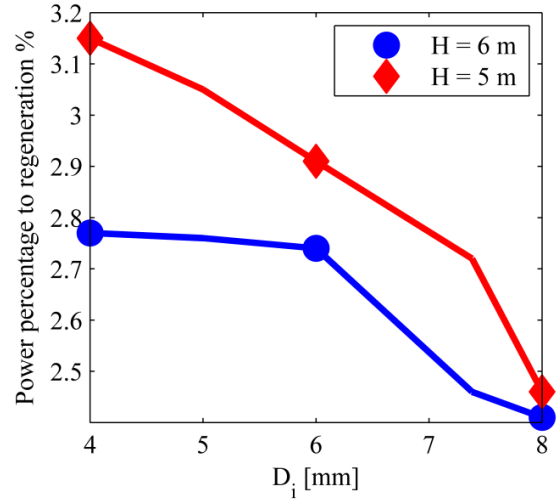

Fig. 15. Regenerative heat transfer.

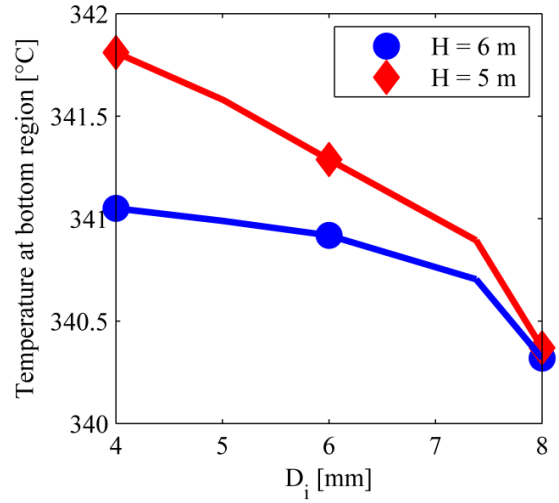

Fig. 16. Water temperature in the inversion region.

V. CONCLUSIONS

In the present paper the bayonet tube steam generator designed for ALFRED has been analyzed from the thermal and hydraulic point of view. The objective of the study was to analyze the effect of some characteristic bayonet parameters on the steam generator performance. The investigated parameters are the insulation between the fluid in the inner pipe and the fluid in the annular gap, the size of the inner tube and the length of the bayonet. The analysis has shown that the length of the bayonet tube plays an important role on the performance of the component: in all the cases considered in this paper the longest bayonet tube has the better results; therefore it is suggested to increase as much as possible the length of the bayonet tube in agreement with the design constraints. The regenerative heat transfer worsen the steam generator

performance, because it deteriorates the steam quality. In order to take advantage of the annular configuration for the heat transfer it is important to prevent as much as possible this effect approaching the adiabatic limit condition. Finally, the analysis on the size of the internal tube has revealed the necessity to consider carefully the connection between the heat transfer coefficient inside the annular gap and the pressure drops of the fluid, so to reach a suitable trade-off between these quantities.

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