Proceedings of International Conference on Heat Exchanger Fouling and Cleaning - 2015 (Peer-reviewed)
June 07 - 12, 2015, Enfield (Dublin), Ireland
Editors: M.R. Malayeri, H. Müller-Steinhagen and A.P. Watkinson

Published online
www.heatexchanger-fouling.com

A METHODOLOGY TO SIMULATE THE IMPACT OF TUBE FOULING ON STEAM GENERATOR PERFORMANCE WITH A THERMAL-HYDRAULIC CODE

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ABSTRACT

Corrosion product deposits in the secondary side of nuclear plant steam generators may result in tube fouling. Tube fouling is a deposit on the tube surfaces which is influential for the heat exchanges between the primary and the secondary circuits. It may cause a steam pressure decrease and induce a power reduction in the case of large deposits. The main objective of this paper is to present a methodology to simulate the impact of tube fouling on steam generator performances such as steam pressure level. Simulations are performed with THYC, which is EDF reference code for the modeling of two-phase thermal-hydraulic flows in 3D at the subchannel scale. A subchannel scale is a mesoscale which allows numerical simulations in whole nuclear components such as steam generators within acceptable computation times. Tube fouling induces an additional thermal resistance between the primary and the secondary circuits. In this paper, the thermal resistance is supposed to correspond to the conductive resistance of a dense deposit by using the Maxwell model for a continuous solid phase with inclusions. As fouling deposit thicknesses are not uniformly distributed on the tube bundle, several thermal resistance distributions are investigated. Simulated thermal-hydraulics and calculated performance parameters are examined. In most cases, tube fouling concentrated in hot leg is the most influential distribution. Nevertheless, for a large amount of deposits, tube fouling uniformly distributed in both hot and cold legs becomes more influential. This simulation series could be an initial step to numerically quantify the tube fouling impact on steam generator performances. The associated limits and the strategy to improve the thermal resistance model are discussed.

INTRODUCTION

Electricité de France (EDF) derives about 80 % of its electricity from nuclear energy. It operates 58 Pressurized Water Reactors (PWR). Safety and performance of these reactors are crucial to ensure an electrical supply to the whole national territory. The steam generators (Fig. 1) are heat exchangers interfacing with the primary and the secondary flows. They play an important role as a safety barrier.

Each steam generator has a high number of reversed-U tubes, between 3300 and 5600 tubes according to the type of steam generator. The primary flow comes from the nuclear reactor core and circulates inside the tubes. A pressure equal to 15.5 Mpa is maintained in this flow to avoid boiling phenomena in the core. The secondary flow circulates outside the tubes through the bundle. This flow boils through contact with the tubes in order to produce steam. This steam allows to produce electricity. The tubes are supported by several plates called “tube support plates”. Flow holes allow the secondary flow to circulate through these plates. At the top of the tube bundle, separators separate the remaining liquid phase from the steam phase. Each steam generator is divided in two main parts: the hot leg and the cold leg. The primary flow circulates upward in hot leg, while it circulates downward in cold leg.

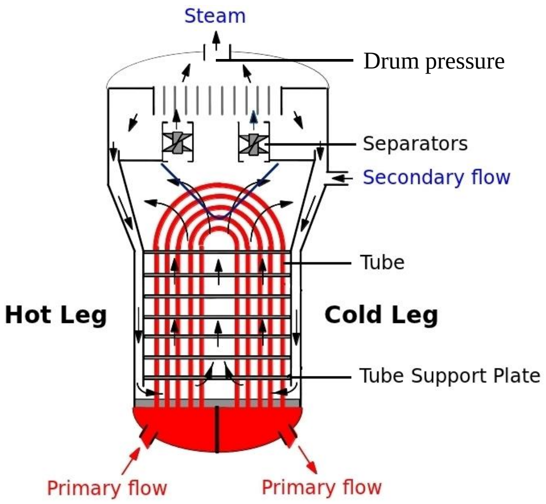

Fig. 1 Schematic principle of a steam generator

Several components are affected by corrosion phenomena in different parts of the PWR secondary circuit. A relatively high quantity of corrosion products is therefore produced and circulates in the secondary flow. Moreover impurities from make-up water, auxiliary feed-water and condenser leaks also circulate in the secondary flow. All those materials are convected by the liquid phase inside the steam generator. As corrosion products are non-volatile, they cannot be transported out of the steam generator by the steam phase, those materials mainly remain inside the steam generator and produce deposits (Corredera et al., 2008). Only a little part of them can be removed through the permanent blow-down of the steam generator.

Two different kinds of deposits have been found in the steam generators according to their location on tubes or on tube support plates. In this paper we specifically focus on tube fouling. Tube fouling is a deposit on the outer tube surfaces (Fig. 2). This kind of deposit is supposed to be responsible for heat exchange degradations between the primary and the secondary flows (Varrin, 1996). As deposits grow, an additional thermal resistance is introduced between the primary and the secondary flows. This resistance can decrease the thermal performances of steam generators.

Fig. 2 Photo of tube fouling (hot leg on the right side) – Source EDF CEIDRE

In-operation monitoring is made on the EDF fleet in order to control the behavior and the performance of each steam generator (Bertrand et al., 2012). Temporal evolutions of different performance parameters are measured during operation periods of steam generators. An important database is therefore available in EDF and analyzed. One of these measurements is the outlet steam pressure, also called drum pressure. It represents the outlet pressure at the top of steam generators (Fig 1). Tube fouling has an important impact on the drum pressure value. Nevertheless this impact is difficult to predict. The kinetics generally tend to decrease on a long-term basis compared to their initial value (steam generator without any fouling deposit) but quite significant variations can be observed during one operating cycle (pressure drop after a plant trip for instance).

Otherwise a code, called THYC (ThermoHYdraulique des Composants), has been developed by the EDF R&D Division. THYC is the EDF's reference three dimensional thermal-hydraulic code which simulates two-phase flows and heat exchanges at the subchannel scale for industrial heat exchangers. A subchannel scale is a mesoscale which has the advantage to allow thermal-hydraulic flow calculations in whole nuclear components with acceptable computation times, from a few minutes to a few hours depending on the mesh refinement. This code is mainly used to ensure the performances and the safety of PWR. In this paper, the THYC code has been used for steam generators (David, 1999; David, 1996). It is based on a three dimensional modeling of the fluid circulating outside the tubes (secondary flow) and a one dimensional thermal modeling of the fluid circulating inside the tubes (primary flow). Applied to a steam generator, the THYC code simulates the secondary thermal-hydraulic flow, the thermal exchanges between the primary and the secondary flows and performance parameters such as the drum pressure.

In this context, a methodology has been developed by the EDF R&D Division in order to simulate the impact of tube fouling on steam generator performance by using the THYC code. A thermal resistance is added on the tube surfaces due to fouling deposits. The associated drum pressure value is then simulated. On the long view, the main objective of such simulations would be to establish a quantitative link between the actual levels of tube fouling observed in some nuclear power plants and the measured drum pressure kinetics.

The thermal-hydraulic model, which has been previously developed and implemented in the THYC code, is presented in this work. A fouling model has been developed on the basis of the Maxwell model for a continuous solid phase with inclusions. This model supposes that the thermal resistance corresponds to the conductive resistance of a dense deposit. As fouling deposition is not uniformly distributed on the tube bundle, several thermal resistance distributions are investigated. Simulated thermal-hydraulics and calculated performance parameters, especially the drum pressure, are examined. This simulation series could be an initial step to numerically quantify the tube fouling impact on steam generator performance. The associated limits and the strategy to improve the thermal resistance model are discussed in the conclusion part.

PHYSICAL MODELLING

Thermal-hydraulic model

Secondary flow. The secondary flow modeling is based on a porous media approach. This approach is obtained by using a space-time averaging of the local conservation equations of mass, momentum and energy for each phase (liquid and steam) in "small" control volumes. Each control volume includes both fluid and solids (Fig. 3). A fluid porosity term ε is then introduced in the equations in order to quantify the proportion between the volume of fluid V and the total volume V_{tot}.

$$\varepsilon = \frac{V}{V_{tot}} \quad (1)$$

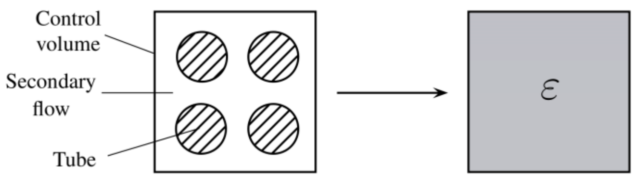

Fig. 3 Porosity in a THYC control volume

Due to the space and time averaging, the liquid and steam phases are not considered as two different phases. They are supposed to be only one fluid with the properties of an homogeneous mixture of liquid and steam. This assumption allows one to calculate 3D thermal-hydraulic data which are relevant for different analysis such as deposit phenomena in steam generators. Nevertheless the level of physical phenomena should not be too local to enable calculations in whole nuclear components with acceptable computation times. Three conservation equations are also obtained for this mixture denoted "m".

Mass conservation:

$$\frac{\partial}{\partial t}(\varepsilon\rho_m)+div(\varepsilon\rho_m U_m)=0 \qquad (2)$$

Momentum conservation:

$$\frac{\partial}{\partial t}(\varepsilon\rho_m U_m)+div(\varepsilon\rho_m U_m \otimes U_m)+div(\varepsilon\rho_m C_l C_v U_r \otimes U_r) \qquad (3)$$
$$=-\varepsilon grad(P_m)+div(\varepsilon\tau_m)+\varepsilon\rho_m g+I_{ts}$$

Energy conservation:

$$\frac{\partial}{\partial t}(\varepsilon\rho_m H_m)+div(\varepsilon\rho_m H_m U_m)+div(\varepsilon\rho_m C_l C_v L U_r) \qquad (4)$$
$$=\varepsilon\frac{\partial P_m}{\partial t}-div(\varepsilon\phi_m)+\varepsilon\frac{4}{d_{th}}h_{ts}(T_{to}-T_s)$$
$$+\varepsilon\left(U_m+C_l C_v\rho_m\left(\frac{1}{\rho_v}-\frac{1}{\rho_l}\right)U_r\right)grad(P_m)$$

Complementary equations or closure relations are needed to solve this system of three equations. They are obtained by making assumptions such as: the two phases are supposed to be at saturation. The relative velocity between phases is given using an empirical correlation based on a drift flux model. Moreover, additional models are given to calculate local and distributed head losses and heat transfer taking account of the local flow regime.

Primary flow. The primary flow modeling is limited to one energy conservation equation. It means that only the one-phase flow temperature inside the tubes is calculated by the THYC code. The hydraulic flow has to be defined as boundary conditions by the users: pressure and flow rates. Moreover the tubes are grouped in "classes" due to their large number in a heat exchanger such as a steam generator. The thermal behavior of the primary flow is supposed to be identical in each class. This modeling strategy limits the calculation time.

Energy conservation:

$$\frac{\partial T_p}{\partial t}+\frac{Q_p}{\rho_p}\frac{\partial T_p}{\partial s}=-\frac{4}{\rho_p Cp_p d_{ti}}h_{tp}\left(T_p-T_{ti}\right) \qquad (5)$$

Tubes. The heat exchange between the primary and the secondary flows occurs through tubes. The energy conservation equation in these tubes can be written:

$$\frac{\partial\Phi}{\partial t}+div(\phi_m)=W \qquad (6)$$

where Φ [J.m^{-3}] is the energy per unit volume or energy density; ϕ_m [W.m^{-2}] is the conductive heat flux; W [W.m^{-3}] is the volumetric thermal power (= 0 for tubes of steam generators).

In isotropic materials, the conductive heat flux is calculated by an empirical law of heat conduction also known as Fourier's law:

$$\phi_m=-k\,grad(T) \qquad (7)$$

where k [W.m^{-1}.K^{-1}] is the thermal conductivity which depends on the material and its temperature.

As shown in Fig. 4, the interface between the tube and the primary flow is modeled by the following equation:

$$\phi_m.n_{tp}=h_{tp}\left(T_{ti}-T_p\right) \qquad (8)$$

where n_{tp} is the normal of the inner tube surface; h_{tp} [W.m^{-2}.K^{-1}] is the heat transfer coefficient between the tube and the primary flow; T_{ti} [K] is the inner tube temperature; T_p [K] is the primary temperature.

In the same way, the interface between the tube and the secondary flow is modeled by the following equation:

$$\phi_m.n_{ts}=h_{ts}\left(T_{to}-T_s\right) \qquad (9)$$

where n_{ts} is the normal of the outer tube surface; h_{ts} [W.m^{-2}.K^{-1}] is the heat transfer coefficient between the tube and the secondary flow; T_{to} [K] is the outer tube temperature; T_s [K] is the secondary temperature.

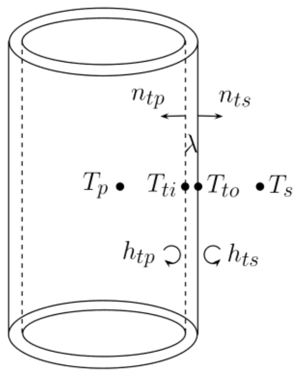

Fig. 4 Interfaces between the tube and the primary / secondary flows

In the nominal case, the steam generator tube surfaces are supposed to be "clean", without any deposit on tubes. The heat transfer coefficients h_{tp} and h_{ts} are calculated by correlations available in the literature. In the THYC code, different correlations are used depending on the flow regime and its main direction. Let h_{tp}^{clean} and h_{ts}^{clean} denote these heat transfer coefficients. Obvious relations are obtained:

$$h_{tp} = h_{tp}^{clean} \tag{10}$$

$$h_{ts} = h_{ts}^{clean} \tag{11}$$

After an operation period, the steam generator tube surfaces cannot be supposed to be “clean” anymore. Deposit phenomena may have taken place in different parts, especially on tubes. The steam generator is fouled. A thermal resistance, called fouling resistance and denoted R_f [$m^2.K.W^{-1}$], is added in the physical modeling in order to take into account the presence of these deposits. As they are thermally in series with the tube walls, the thermal resistance associated to the heat transfer coefficient h_{ts} is equal to the sum of the thermal resistance associated to the heat transfer coefficient h_{ts}^{clean} and the fouling resistance:

$$h_{ts} = \frac{1}{1/h_{ts}^{clean} + R_f} \tag{12}$$

Fouling resistance model

In this paper, a model has been developed to quantify the fouling resistance. This model is based on several assumptions which are detailed below. The limits and perspectives are discussed in the conclusion part.

Assumptions. The deposit is supposed to be a dense layer with a given porosity denoted ε_f. This porosity is different from the fluid porosity which is introduced in the THYC code model (equation (1)). The dense layer can be created by particle deposition and consolidation mechanisms due to soluble species precipitation (Turner et al., 1997). The potential porous layer, which can be created on the dense layer, is not taken into account in this paper. This assumption allows one to develop a simplified model.

The model assumes that the deposit is only made up of magnetite. This element has been predominantly found in deposits inside steam generators. Although minority species such as copper for example have been also found, they are not taken into account in this paper. Moreover the pores of deposits are supposed to be filled with saturated steam. This assumption maximizes the fouling resistance because the steam thermal conductivity is lower than the water thermal conductivity.

The impact of deposits on steam generator thermal-hydraulics is only considered through an additional thermal resistance between the primary and the secondary flows. In other words, the fouling deposit cannot directly impact the flow due to its own presence. Moreover the increase of the total heat exchange surface due to the growth of deposits on tubes is neglected.

The steam generator is supposed to operate at steady nominal conditions.

Model. Thanks to these assumptions, the fouling resistance corresponds to a conductive resistance. The associated thermal conductivity denoted k_f is calculated by using the Maxwell model for a continuous solid phase with inclusions. It has been introduced in (Pujet et al., 2004):

$$k_f = k_{mg}\left(1 + \frac{3\varepsilon_f}{\left(\frac{k_v + 2k_{mg}}{k_v - k_{mg}}\right) - \varepsilon_f}\right) \tag{13}$$

where k_{mg} [$W.m^{-1}.K^{-1}$] is the thermal conductivity of magnetite; k_v [$W.m^{-1}.K^{-1}$] is the thermal conductivity of steam at the saturation temperature denoted T_{sat} in the steam generator secondary flow. The thermal conductivity of magnetite is estimated at the saturation temperature by the following expression (Varrin, 1996), with T_{sat} in °C:

$$k_{mg} = 3.86 - 0.00137 T_{sat} \tag{14}$$

The fouling resistance is then calculated from the thickness of the fouling deposit denoted e_f [m] at the considered location inside the steam generator:

$$R_f = \frac{e_f}{k_f} \tag{15}$$

SIMULATION RESULTS

Distribution of tube fouling

Several “extreme” spatial distributions of tube fouling have been investigated in this paper. The first objective is to estimate the maximum impact on steam generator performances. The second objective is to perform a comparison between these distributions in order to quantify their specific impact. The notion of equivalent thickness of deposit has been introduced to make this comparison physically consistent. It means that the total mass of fouling deposit inside the steam generator is identical for each considered equivalent thickness. For example, if a distribution of tube fouling is considered on half the tube bundle, the real thickness of deposit used in equation (15) is doubled as compared to an uniform distribution of tube fouling on the whole tube bundle. The total masses of deposit are also identical in both cases.

Six “extreme” spatial distributions have been considered:

- one distribution called “Uniform”: deposits are uniformly distributed on the whole tube bundle;

- three distributions called "Top", "Middle" and "Bottom": deposits are respectively distributed at the top-third, at the middle-third and at the bottom-third of the tube bundle. As the deposit surface is divided by three compared to the "Uniform" distribution, the real thickness of deposit is multiplied by three;
- two distributions called "Hot Leg" and "Cold Leg": deposits are respectively distributed in hot leg and in cold leg of the tube bundle. As the deposit surface is divided by two compared to the "Uniform" distribution, the real thickness of deposit is multiplied by two.

Estimation of modeling parameters

Different equivalent thicknesses of deposit have been investigated in this paper: {0; 10; 20; 30; 40; 50; 60; 70; 80; 90; 100} µm. An equivalent thickness equal to 0 µm means a "clean" steam generator without any fouling deposit. It might be new steam generator or a steam generator entirely cleaned by a chemical process for example. On the contrary an equivalent thickness equal to 100 µm means a highly fouled steam generator. It can represent a total mass of deposit equal to a few tones; such a mass has been previously observed in some steam generators on the EDF fleet.

The fouling deposit porosity is not well-estimated in steam generators. Moreover its value is probably non-uniform on the tube bundle of each steam generator. As this parameter has a significant impact on the fouling resistance estimate (Fig. 5), an assumption has been made in order to maximize the fouling resistance. As the thermal conductivity of magnetite is higher than the thermal conductivity of steam, the higher the value of porosity is, the higher the fouling resistance is. A quite high value of porosity equal to 0.35 has been estimated. We can mention that this value has a physical meaning.

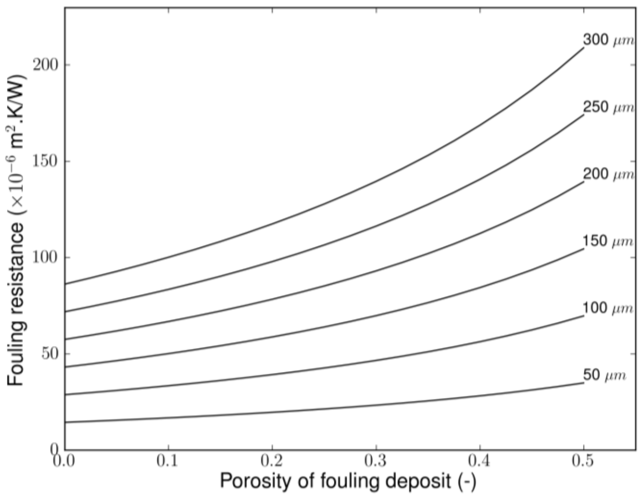

Fig. 5 Graph of the fouling resistance for different values of porosity and for several deposit thicknesses

The saturation temperature and the thermal conductivity of steam have a low impact on the fouling resistance in steam generator conditions. The values of these parameters are respectively equal to 275 °C and 0.06 W.m^{-1}.K^{-1}.

Simulations

Drum pressure. The drum pressure has been simulated according to the equivalent thickness of deposit for the six investigated distributions previously mentioned (Fig. 6). A total of 61 simulations has been performed with the THYC code. It is important to mention that the total thermal power is identical for each simulation. It is equal to about 930 MW. Moreover identical pressure, mass flow and temperature are defined as boundary conditions for the primary flow. Pressure and enthalpy are defined as boundary conditions for the secondary flow.

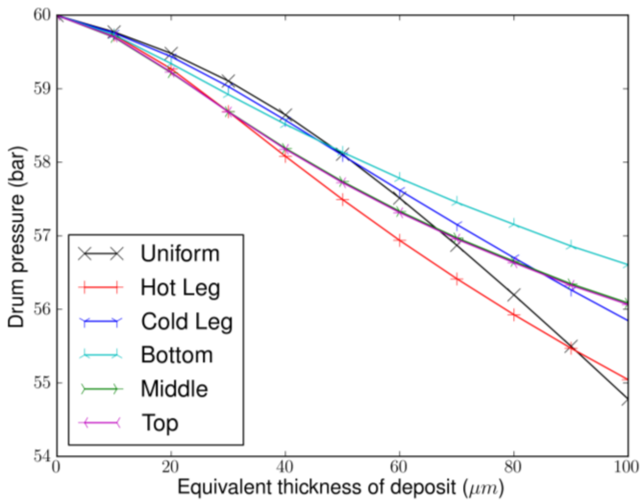

Fig. 6 Graph of the drum pressure simulated by the THYC code according to the equivalent thickness of deposit for the six "extreme" spatial distributions of tube fouling

The obtained results underline two dominant trends. Firstly the higher the equivalent thickness of deposit is, the more the drum pressure decreases for each investigated distribution of tube fouling. This decrease is included between 3 bars and a little bit more than 5 bars for an equivalent thickness equal to 100 µm. We need to look at this relatively important decrease against the different assumptions of fouling resistance maximization previously mentioned. Secondly the spatial distribution of tube fouling has a non-negligible impact on the drum pressure decrease.

For a low tube fouling (equivalent thickness of deposit lower than 30 µm), the "Hot Leg", "Bottom", and "Top" distributions are the most influential distributions, while the "Uniform" distribution is the least influential distribution. For an intermediate tube fouling (equivalent thickness of deposit included between 30 µm and 50 µm), the "Hot Leg" distribution is the most influential distribution and the "Uniform" distribution is almost as influential as the "Cold Leg" and "Bottom" distributions. For a high tube fouling (equivalent thickness of deposit included between 50 µm and 90 µm), the "Hot Leg" distribution is still the most influential distribution but we can see that the "Uniform" distribution becomes the second most influential distribution. For a very high tube fouling (equivalent thickness of deposit higher than 90 µm), the "Uniform" distribution is the most influential distribution. In conclusion the "Hot Leg" distribution is the most influential distribution until a high tube fouling, while it is the "Uniform" distribution for a very high tube fouling. On the contrary the "Uniform" distribution is the least influential distribution until an intermediate tube fouling, while it is the "Bottom" distribution for a high and a very high tube fouling.

Temperature. Mean primary and secondary flow temperatures have been simulated versus altitude all over the steam generator according to the equivalent thickness of deposit. Profiles deduced from simulations are only presented for the most influential distributions ("Hot Leg" and "Uniform" distributions) as shown in Fig. 7 and 8. The mean primary flow temperature progressively decreases when it circulates inside the tubes. The mean secondary flow temperature becomes rapidly constant when it circulates outside the tubes through the bundle. This flow boils at a constant temperature equal to the saturation temperature.

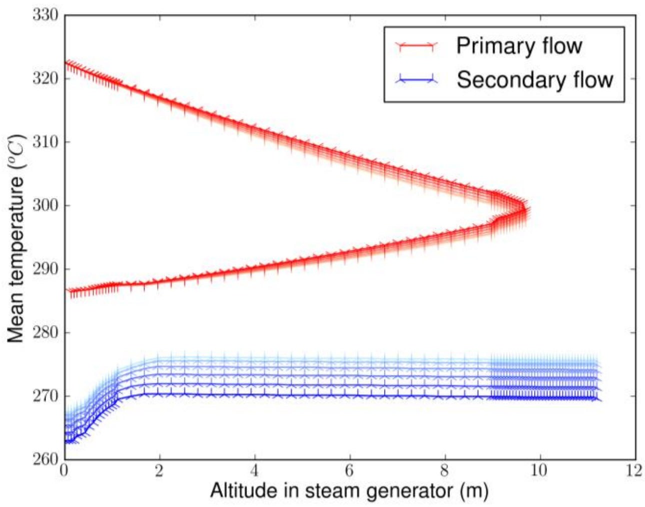

Fig. 7 Profiles of mean primary and secondary flow temperatures according to the equivalent thickness of deposit for the "Uniform" distribution (light colors are used for the lowest equivalent thicknesses, dark colors are used for the highest equivalent thicknesses)

The higher the equivalent thickness of deposit is, the more the mean secondary flow temperature at a given altitude decreases. This phenomenon has a physical meaning. When the equivalent thickness of deposit increases, the fouling resistance also increases and the global heat transfer is penalized. As the total exchanged power is kept constant in the steam generator, the mean temperature difference between the primary and the secondary flows has to increase. As the primary flow temperature (i.e. primary water temperature at the inlet and outlet of the steam generator) is imposed by the nuclear core reactor control, the secondary flow temperature decreases. This temperature decrease is more important for the "Hot Leg" and "Uniform" distributions compared to the other considered distributions.

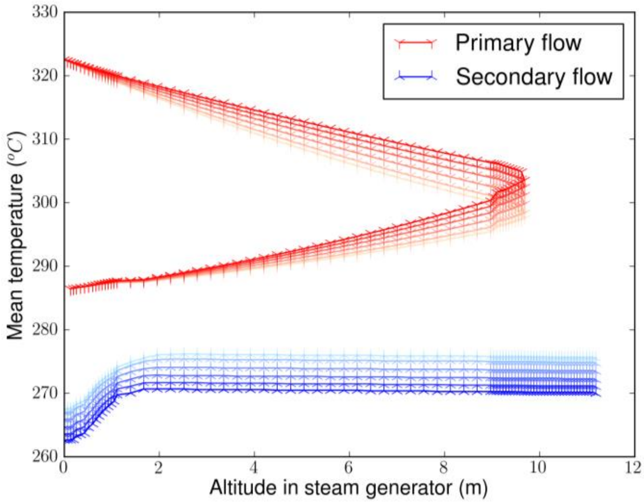

Fig. 8 Profiles of mean primary and secondary flow temperatures according to the equivalent thickness of deposit for the "Hot Leg" distribution (light colors are used for the lowest equivalent thicknesses, dark colors are used for the highest equivalent thicknesses)

For the "Hot Leg" distribution, the profile of mean primary flow temperature is strongly affected. Without any fouling deposit, the primary flow temperature mainly decreases in hot leg. This decrease is equal to about 20 °C in hot leg, while it is equal to about 10 °C in cold leg. With the presence of fouling deposits, the heat transfer becomes more important in cold leg in order to counterbalance the heat transfer penalization in hot leg. For an equivalent thickness of deposit equal to 100 µm, the temperature decrease is similar in hot leg and in cold leg. It is equal to about 15 °C in each leg. The heat transfer is penalized in a steam generator part where it is supposed to be maximum in nominal operating conditions, that is to say in hot leg. As a consequence, the steam drum pressure decreases for the "Hot Leg" distribution as soon as initial fouling deposits begin to grow (Fig. 6).

For the "Uniform" distribution, the profile of mean primary flow temperature is less affected compared to the "Hot Leg" distribution. This profile is approximately identical for each equivalent thickness of deposit because the heat transfer is uniformly penalized on the whole tube bundle. No steam generator part can counterbalance the heat exchange penalization due to fouling deposits. It may explain the drum pressure decrease presented in Fig. 6. For a low tube fouling, the "Uniform" distribution has a very limited impact because the value of fouling resistance is relatively low all over the steam generator tube bundle. On the contrary for a high or a very high tube fouling, the value of fouling resistance becomes relatively important and the drum pressure highly decreases.

Energy. Simulations of the energy distribution received by the secondary flow for a very high tube fouling (equivalent thickness of deposit equal to 100 µm) are presented in Fig. 9 and 10. The energy distribution is almost identical between a “clean” steam generator (without any fouling deposit) and the “Uniform” distribution of tube fouling whatever the equivalent thickness of deposit. On the contrary the energy distribution is strongly affected by the “Hot Leg” distribution. The energy received in cold leg by the secondary flow gradually increases when fouling deposits grow in hot leg.

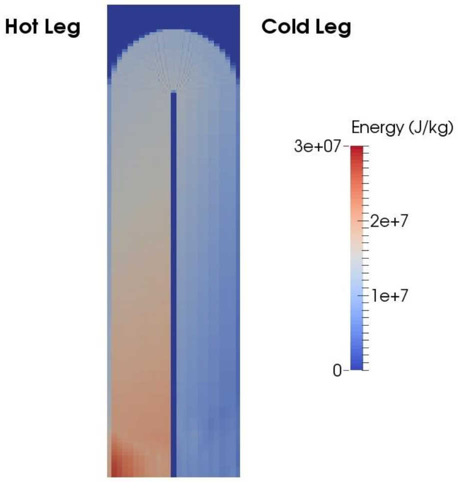

Fig. 9 Energy received by the secondary flow with an equivalent thickness of deposit equal to 100 µm for the “Uniform” distribution

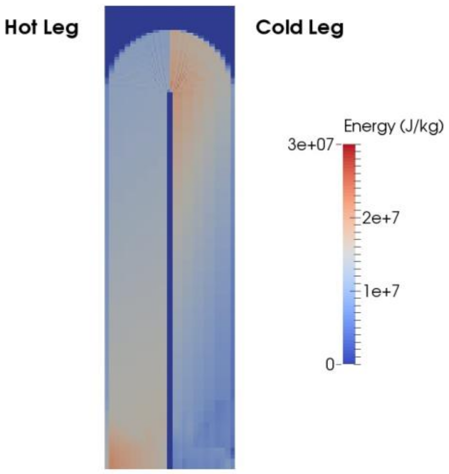

Fig. 10 Energy received by the secondary flow with an equivalent thickness of deposit equal to 100 µm for the “Hot Leg” distribution

CONCLUSION

Tube fouling in nuclear power plants is a concern for EDF and motivates the R&D to develop a methodology in order to simulate its impact on steam generator performance. Simulations have been performed by means of the THYC code. It is the EDF reference code for the modeling of two-phase thermal-hydraulic flows in 3D at the subchannel scale for whole nuclear components (such as steam generators) within acceptable computation times. A fouling model has been developed on the basis of the Maxwell model for a continuous solid phase with inclusions. This model supposes that the thermal resistance corresponds to the conductive resistance of a dense deposit. As fouling deposits are not uniformly distributed on the tube bundle, several thermal resistance distributions have been investigated.

The simulation results obtained in this work underline two dominant trends. Firstly the higher the thickness of deposit is, the more the drum pressure decreases for each investigated distribution of tube fouling. This is consistent with the developed fouling resistance model which necessarily increases the thermal resistance on tubes. Secondly the spatial distribution of tube fouling has a non-negligible impact on the drum pressure decrease. The “Hot Leg” distribution is the most influential distribution to the point of a high tube fouling, while it is the “Uniform” distribution for a very high tube fouling. On the contrary, the “Uniform” distribution is the least influential distribution until an intermediate tube fouling, while it is the “Bottom” distribution (i.e. in the lower third of the tube bundle) for a high and a very high tube fouling.

One of the main limits of this work is related to the developed fouling resistance model which is relatively simplified. Actually this thematic is complex and the associated literature is relatively limited. Despite that, two suggestions are proposed in this conclusion. They might help to make significant improvements. Firstly future works could be performed on the development of a “full” model which would more precisely simulate the heat transfer phenomena inside deposits (Uhle, 1991) (Turner et al., 2000), especially inside porous deposits. Indeed the heat transfer inside such deposits could be enhanced due to the creation of new nucleation sites or boiling chimneys for example. The development of a “full” model could calculate a better fouling resistance estimate induced by these deposits from the knowledge of their physicochemical properties. Secondly a more detailed analysis of physical phenomena impacting the physicochemical properties of fouling deposits would allow one to define objective criteria to determine the fouling resistance evolution observed during one operation cycle.

A longer-term perspective would be to couple (or a minima to connect) the thermal-hydraulics with a deposit model (Moleiro et al., 2010; Prusek et al., 2013). This model aims to predict the localization and the growth rate of deposits such as tube fouling. It requires to calculate 3D distributions of the chemical parameters that have a major contribution, together with heat transfer, on deposition rates. It allows one to simulate deposit thickness distributions in 3D on the whole tube bundle. Fouling resistance distributions could be deduced from a previously developed fouling resistance model. Such simulations would improve our knowledge of tube fouling kinetics and associated drum pressure evolutions.

NOMENCLATURE

C quality [-]
C_p thermal capacity [J.kg^{-1}.K^{-1}]
d_{th} thermal diameter [m]
d_{ti} inner diameter of tubes [m]
e_f fouling deposit thickness [m]
g gravity [m.s^{-2}]
h_{tp} tube side heat transfer coefficient [W.m^{-2}.K^{-1}]
h_{ts} shell side heat transfer coefficient [W.m^{-2}.K^{-1}]
H enthalpy [J.kg^{-1}]
I_{ts} secondary fluid/solids interaction term [kg.m^{-2}.s^{-2}]
k thermal conductivity [W.m^{-1}.K^{-1}]
L latent heat of vaporization [J.kg^{-1}]
n_{tp} normal of the inner tube surface [-]
n_{ts} normal of the outer tube surface [-]
P pressure [Pa]
Q mass flow rate [kg.m^{-2}.s^{-1}]
R_f fouling resistance [m^2.K.W^{-1}]
t time [s]
T temperature [K]
T_{ti} inner tube temperature [K]
T_{to} outer tube temperature [K]
U velocity [m.s^{-1}]
U_r relative velocity [m.s^{-1}]
W volumetric thermal power [W.m^{-3}]
ε fluid porosity [-]
ε_f fouling deposit porosity [-]
ρ mass density [kg.m^{-3}]
τ_m viscous, turbulent stress tensor [kg.m^{-1}.s^{-2}]
Φ energy density [J.m^{-3}]
ϕ_m conductive heat flux [W.m^{-2}]

Subscripts

f fouling deposit
i inner
l liquid
m mixture
mg magnetite
o outer
p primary fluid
s secondary fluid
sat saturation
t tube
v vapor (or steam)

REFERENCES

Bertrand, P., Gay, N., and Crinon, R., 2012, EDF Steam Generators Fleet: In-operation Monitoring of TSP Blockage and Tube Fouling, *Seventh CNS International Steam Generators to Controls Conference*, Toronto, November.

Corredera, G., Alves-Vieira, M., and De Bouvier, O., 2008, Fouling and TSP blockage of steam generators on EDF fleet: identified correlations with secondary water chemistry and planned remedies, *International Conference on Water Chemistry of Nuclear Reactor Systems*, Berlin, September.

David, F., 1996, THYC, a thermal hydraulic code for steam generators heat exchangers and condensers, *Fourth International Conference on Nuclear Engineering (ICONE-4)*, New Orleans.

David, F., 1999, Three dimensional thermal-hydraulic simulation in steam generators with THYC exchangers code: application to the USTG model 73/19, *Ninth International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-9)*, San Francisco, October.

Moleiro, E., Oukacine, F., and Adobes, A., 2010, Secondary fouling and tube support plate flow blockage: a model based on transport equations, *International Conference on Steam Generator Management Program*, San Antonio, March.

Prusek, T., Moleiro, E., Oukacine, F., Adobes, A., Jaeger, M., and Grandotto, M., 2013, Deposit models for tube support plate flow blockage in Steam Generators, *Int. J. Nuclear Engineering and Design*, Vol. 262, pp. 418-428.

Pujet, S., Rodet, and I., Dijoux, M., 2004, Modeling of the Combined Effects of Particle Deposition and Soluble Iron Precipitation on PWR Steam Generator Fouling, *International Conference on Water Chemistry of Nuclear Reactor Systems*, San Francisco, October.

Turner, C.W., Klimas, S.J., and Brideau, M.G., 2000, Thermal resistance of steam-generator tube deposits under single-phase forced convection and flow-boiling heat transfer, *Canadian Journal of Chemical Engineering*, Vol. 78, pp. 53-60.

Turner, C.W., Blimkie, M.E., and Lavoie, P.A., 1997, Physical and Chemical Factors Affecting Sludge Consolidation, *AECL-11674 COG-96-492-1*.

Uhle, J.L., 1991, Boiling Heat Transfer Characteristics of Steam Generator U-Tube Fouling Deposits, *MIT Thesis*.

Varrin, R., 1996, Characterization on PWR Steam Generator Deposits, *EPRI TR-106048*, February.