DEPOSIT MODEL FOR TUBE SUPPORT PLATE BLOCKAGE IN STEAM GENERATORS

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Abstract

Corrosion product deposits in the secondary side of nuclear plant steam generators may result in tube support plate blockage, and tube fouling. In order to improve our understanding of those two phenomena, a solid deposit growth model has been developed by the R&D Division of EDF. The validity of this model is tested by comparing the results of simulations to the actual levels of tube support plate blockage observed in some nuclear plants. The limits of the model and the strategy to improve it are discussed.

1 Introduction

Electricité de France (EDF) nowadays operates 58 Pressurized Water Reactors (PWR) which represent more than sixty three thousand MW of installed power capacity and more than 85 % of electricity produced in France. Safety and performance of these reactors are crucial targets to ensure electrical supply to the whole national territory. Steam Generators (SGs) play a crucial role in this domain both as a safety barrier and as a thermal energy exchanger from the primary to the secondary circuit.

Deposition of corrosion products on the surfaces of SG components affects the SG behaviour. Tube fouling can induce a loss of efficiency due to a decrease in steam pressure at the SG outlet. EDF has recently experienced a blockage problem of the quatrefoil Tube Support Plates (TSPs) in some SGs, inducing tube leakage events on EDF fleet.

In this context, our study describes an EDF R&D effort to specify and implement a model for the growth of solid deposits on the secondary side of SGs, and more specifically on their TSPs, in EDF thermal-hydraulic reference code, THYC. The aim of this model is to predict the localization and the growth rate of deposits in order to simulate tube fouling as well as TSPs foils clogging.

2 Fouling and TSP blockage of Steam Generators

The degradation of some secondary circuit surfaces and drain systems in PWR induces the circulation of corrosion products, metallic oxides, in the secondary circuit. Impurities and contaminants from make-up water, auxiliary feed-water and condenser leaks, are also introduced into the secondary side of the plant. Those materials can be transported to the SG and converted into deposits on SG surfaces [1].

These deposits are supposed to be responsible for many detrimental effects which affect the SGs efficiency. For instance, a detrimental effect is the fouling of SG tubes which is penalizing for the heat exchanges.

Another problem is associated with deposits formed on the secondary side of Nuclear Power Plants (NPPs). Between 2004 and 2006, three primary to secondary leaks occurred at one plant in France. The thermal-hydraulic and vibration studies confirmed a cracking mechanism caused by Flow-Induced Vibrations resulting in a circumferential crack. Those studies pointed out the role of an aggravating factor : the blockage of the quatrefoil areas of the upper TSPs by deposits. One of the solutions developed in EDF is to perform fundamental studies in order to understand and point out the root causes of fouling and flow blockage phenomena at the “component scale”.

We call “component scale” a scale which is an intermediate scale between the macroscopic scale and the microscopic scale. In comparison with the microscopic scale, this scale has the advantage to calculate the global effect of blockage rate on thermal-hydraulics. In comparison with the macroscopic scale, it takes into account local thermal-hydraulic parameters which are at the right scale to understand the blockage phenomenon. Even if this scale does not allow one to understand locally fouling and flow blockage, it seems to be a relevant scale to simulate those phenomena in the whole SG. At this scale, it seems moreover natural to study both fouling and TSP flow blockage simultaneously for two reasons. Firstly the same source is responsible for fouling deposits on the free span of the tubes and within the flow holes. Secondly the fundamental mechanisms of those phenomena are basically similar : deposition, consolidation and removal. On the basis of the three dimensional thermal-hydraulic code THYC, a model of SG fouling had been previously developed. An extension of this model has been implemented in order to specifically assess TSP flow blockage.

3 The THYC code

EDF has developed THYC [2], a three dimensional thermal-hydraulic code, which allows one to simulate two-phase flows and heat exchanges at the “component” scale for industrial heat exchangers. THYC is applicable to different kinds of heat exchangers : single-phase heat exchangers, steam generators and condensers. It is used to improve the performances and guarantee the safety of NPPs.

THYC includes a 3D modelling of the secondary circuit fluid outside the tubes. The primary circuit fluid flowing inside the tubes is modelled by using a 1D thermal equation. The two phases are considered to be one fluid, which is an homogeneous mixture of water and steam. Based on a porous media approach, the THYC model is obtained by using a space-time averaging of the instantaneous equations (mass, momentum and energy) of the mixture phase over control volumes including both fluid and solids. A fluid porosity term ϵ^j is used in the equations to represent the ratio between the fluid volume V_f^j and the total volume V_t^j in each control volume j :

$$\epsilon^j = \frac{V_f^j}{V_t^j} \tag{1}$$

THYC takes into account the relative velocity between liquid and steam, one-phase or boiling heat transfers, as well as thermal coupling between the primary and secondary fluids. It solves three conservation equations of the homogeneous mixture outside the tubes coupled with an energy equation of the fluid inside the tubes. A Finite Volume method on a regular staggered grid is used to solve these equations. On a staggered grid the scalar variables (pressure, density, etc.) are stored in the cell centers of the control volumes, whereas the vectorial variables (velocity, momentum, etc.) are located at the centers of the cell faces.

THYC is used to address industrial problems occurring in the SGs such as heat exchange efficiency. Coupled with a deposit model, it provides the frame to simulate the deposition.

4 The deposit model

4.1 General principles

In this part, all the required thermal-hydraulic data are supposed to be known from a previous THYC calculation even if the growth of deposit such as TSP flow blockage can change SG thermal-hydraulics significantly. A correlation could be used to estimate the effect of TSP flow blockage on thermal-hydraulics but this correlation is not taken into account in this paper.

The deposit model [3] has been developed to estimate the iron oxide deposits on tubes (tube fouling) and TSPs (TSP flow blockage or TSP clogging). These species are introduced in the SG by feed-water, transported by the secondary fluid, deposited on the surfaces, and can be removed by the flow. The deposit model assumes that there is one layer of magnetite deposit with a given porosity. In reality, the deposit can also be made up of minority species such as copper, and the porosity of the deposit is not uniform. The layer of magnetite is created either by particle deposition, or by precipitation of dissolved species into the pores of the deposits. It can be extracted and removed by the flow. The porous layer thickness is calculated as a function of time and space, at each location on tube bundle in the secondary side of SG with two coupled equations :

$$\frac{\partial}{\partial t}(\epsilon^j \rho_m^j C_l^j \Gamma_h^j) + \vec{\nabla}.(\epsilon^j \rho_m^j C_l^j \Gamma_h^j \mathbf{U_l^j}) + \vec{\nabla}.(\mathbf{J_h^j}) = P_h^j + Q_h^j \tag{2}$$

$$\frac{\mathrm{d}m_\delta^j}{\mathrm{d}t} = \sum_{h\in\{p,s\}} \Phi_{\delta,h}^j - \Phi_r^j \tag{3}$$

Equation (2) is a transport equation which allows one to determine the value of the mass fraction Γ_h^j of both suspended particles (h=p) and soluble species (h=s) in water in control volume j. The particles are supposed to have a single size. On the left side of equation (2), the transient term accounts for the accumulation of the quantity $C_l^j \Gamma_h^j$ in the concerned control volume, the convection term and the diffusion term account for the transport of this quantity respectively due to the liquid velocity field U_l^j and the gradient of the mass fraction. On the right side, Q_h^j and P_h^j are the source terms which either create or destroy this quantity, depending of their signs. They respectively represent the volume transfer between the species h and the boundary wall deposit, and the volume transfer between the dissolved species and the particles.

Equation (3) is a local growth equation of deposit layer on the boundary wall. For each deposit phenomenon : tube fouling (δ=f) or TSP flow blockage (δ=c), it allows one to calculate the mass deposited per unit surface area m_δ^j in control volume j from the material flows of particle deposition and soluble species precipitation, denoted $\Phi_{\delta,p}^j$ and $\Phi_{\delta,s}^j$, and the flow of deposits removed Φ_r^j.

The two equations (2) and (3) are not solved with the same time-step because the period of deposition is very long compared with the transport time. The aim of the model is to evaluate the mass deposited on the tubes and tubes support plates from growth equation (3).

The flow of particle deposition is supposed to be equal to the flow of particles transported to the wall and is calculated by using equation (4). In other words, it is assumed that all the particles transported to the wall are deposited on it.

$$\Phi_{\delta,p}^j = K_\delta^j \rho_m^j C_l^j \Gamma_p^j \tag{4}$$

Where K_δ^j is the transport velocity of particles towards the wall due to the overall effect of all the considered mechanisms of transport.

The driving forces models for the soluble species precipitation and the flow of deposits removed are not taken into account in this paper :

$$\Phi_{\delta,s}^j = 0 \tag{5}$$

$$\Phi_r^j = 0 \tag{6}$$

The mechanisms of transport are complex processes which depend on several physical and chemical local parameters. One can therefore not represent them by simple laws, and it is necessary to introduce some empirical correlations taking into account global thermal-hydraulic parameters. Moreover tube fouling and TSP flow blockage are two different phenomena which cannot be physically explained by the same laws. Consequently their mechanisms of transport are different.

4.2 Tube fouling

Tube fouling, which occurs on heated surfaces, seems to be properly described by the overall effect of the following classical mechanisms of transport [4] : diffusion $K_{f,d}^j$, turbulent inertia $K_{f,i}^j$, thermophoresis $K_{f,th}^j$, sedimentation due to gravity $K_{f,se}^j$ and deposition associated with boiling $K_{f,b}^j$.

$$K_f^j = K_{f,d}^j + K_{f,i}^j + K_{f,th}^j + K_{f,se}^j + K_{f,b}^j \tag{7}$$

4.3 TSP flow blockage

The deposit model was firstly developed to predict fouling by simulating the deposition of soluble species and particles on SG tubes. It was secondly extended to predict TSP flow blockage by simulating the deposition of those same species in the flow holes and more specifically on the TSPs [3]. TSP flow blockage, which occurs on unheated surfaces, cannot be described by classical mechanisms of transport. A new deposit model, based on TSP blockage studies [5], has been developed and implemented in the deposit model, and is presented in this part. It takes into account the main physical parameters which affect the growth rate of clogging deposits, such as vapour quality, wall geometry and fluid velocity.

In this paper, we investigate the type of deposit phenomenon described hereafter. The "lipping" phenomenon observed at the inlet of broach holes can be attributed to the presence of a vena contracta where the mainstream flow separates from the wall following a sharp contraction (Figure 1). In the vena contracta, a low-velocity recirculation zone is created beside the support, in which a tiny deposit can begin to grow. The growth of this deposit can be encouraged further by a consolidation process. As the deposit grows, the flow contraction and associated boundary-layer separation will become more severe. The clogging phenomenon tends to become progressively worse.

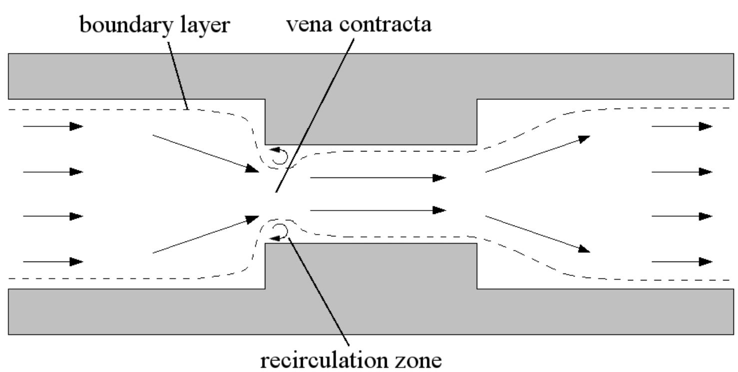

Figure 1: Pattern of vena contracta region

TSP flow blockage is supposed to be exclusively caused by the vena contracta mechanism denoted "v" :

$$K_c^j = K_{c,v}^j \tag{8}$$

The deposition rate constant $K_{c,v}^j$ in each control volume j used to model this mechanism takes into account the main influence parameters such as vapour quality and fluid velocity [5] :

$$K_{c,v}^j = a_v \frac{k_v^j \left(\rho_p - \rho_l^j\right) \left(U_z^j\right)^2 C_g^j d_p^2}{\mu_l^j} \tag{9}$$

Since the vena contracta deposit mechanism depends on the size d_p of particles, different diameters of particles are investigated. The size of particles which circulate in SGs typically range from 0.5 μm to 10 μm [3]. It plays an important role on their transport since little particles are more sensitive to turbulence and bigger to gravity [6]. The vena contracta mechanism is linked to turbulence. Only small particles are therefore taken into account : 0.5 μm, 1 μm, 2 μm and 4 μm.

Above 4 μm this mechanism does not allow to obtain results in agreement with observed data.

Parameter k_v^j allows to take into account that the clogging phenomenon self-sustained and can even accelerate and become progressively worse. The more important the TSP flow blockage rate is, the more this parameter, and so the deposition rate constant of vena contracta, increase :

$$k_v^j = \frac{L - [R(1 - \tau^j)]}{S} \tag{10}$$

The constants L, R and S are characteristic values of the specific geometry of broach holes which represent respectively half the bundle pitch, the equivalent radius of a broach hole and its surface (Figure 2). The calculation of TSP flow blockage rate τ^j in each control volume j is obtained from the results of simulation and is detailed in section 5.

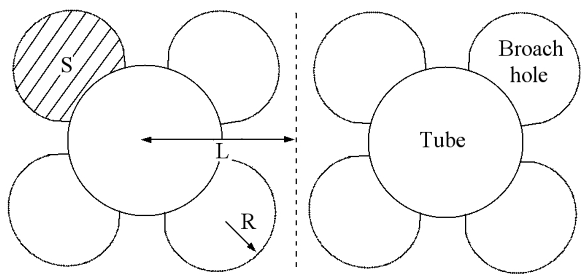

Figure 2: Pattern of a TSP (top view)

The deposition rate constant also depends on a unobservable parameter denoted a_v which is supposed to be constant all over the SG. This unobservable parameter allows one to calibrate the correlation. It could be determined by specific experiments performed on devoted test-facilities but at the steam generator scale and in Pressurized Water Reactors (PWR) conditions, its value is not determined. An inverse method, that could enable one to evaluate this parameter in PWR conditions, by fitting the results of simulations to the actual levels of TSP flow blockage rates observed in some French nuclear plants, is presented in section 6.

5 TSP flow blockage rate

The TSP flow blockage rate is a percentage representing the ratio of flow blockage section to the total hole section. It is dimensionless and is obtained from the results of simulation by using a correlation established from field experience data. This correlation allows one to link the volume of the deposited mass on each flow hole to the blockage rate [3].

Realistic geometries of TSP flow blockage deposits were estimated on the basis of TV inspections which were performed in several French plants. With these geometries, it is possible to estimate a volume of deposit for any TSP flow blockage rate. In practice, control volume j can have several foils and the associated TSP flow blockage rate is supposed to be uniform in each foil of this control volume. The obtained volume of each clogging deposit V_c^j in one foil of control volume j can be related to the rate of flow blockage τ^j by fitting the data according to the expression :

$$\tau^j = \alpha \left(1 - e^{-\beta V_c^j}\right) \tag{11}$$

The values of α and β are respectively 101.66 % and 0.023*10^9 m^{-3}. Some hypothesis on the composition and the porosity of the deposit allow one to estimate the volume of clogging deposit from the deposited mass calculated by equation 3.

In each control volume j, three steps are necessary to calculate the TSP flow blockage rate :

1. Calculation of the thermal-hydraulic data (THYC)
2. Calculation of the deposited mass on the tubes and TSPs (equation (3))
3. Calculation of the flow blockage rate (equation (11))

6 The inverse method

An inverse method has been developed to calibrate the deposit model by fitting the results of it to the actual levels of TSP flow blockage observed in some French nuclear plants [7]. This inverse method aims to evaluate the optimum value of the unobservable parameter a_v which allows to fit the observed data (Figure 3).

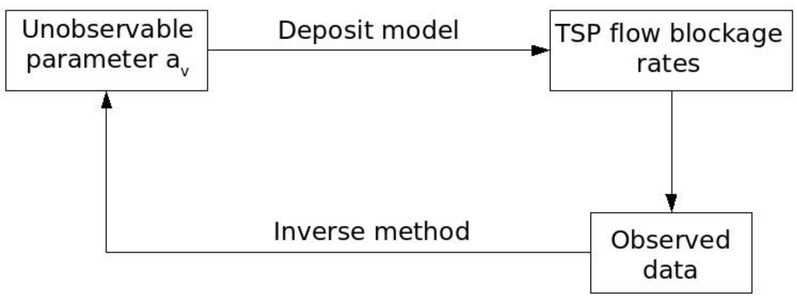

Figure 3: Summary figure of the inverse method

In SGs, the blockage rates observed on the upper TSP can be precisely determined by using a technique of TV Inspection. A camera is inserted in the top of the SG and allows to visualize reliably local blockage rates on this TSP. This technique cannot be used for any other TSP because the controls do not reach those places. Although other techniques like Eddy Currents or Wide Range Level evolution allow one to estimate some mean values of TSP blockage rates in most locations of the SG, the uncertainties are larger. Only blockage rates observed on the upper TSP are therefore taken into account : 422 local values.

These local blockage rates, the thermal-hydraulic quantities calculated by the THYC code and an initial guess (equal to 10^{-3}) for the unobservable parameter a_v are the input data of the inverse method (Figure 4). An inverse model allows one to calculate a new value of a_v which allows an optimum fitting of the observed data. Then a convergence criterion η equal to the relative variation between two consecutive calculations of a_v is estimated. If it is higher than 10^{-4}, the process will iterate one more time. Otherwise the process will stop and the optimum value of a_v is found. In other words this optimum value of a_v associated with the deposit model allows one to derive the simulated TSP flow blockage rates that are closest to the observed blockage rates.

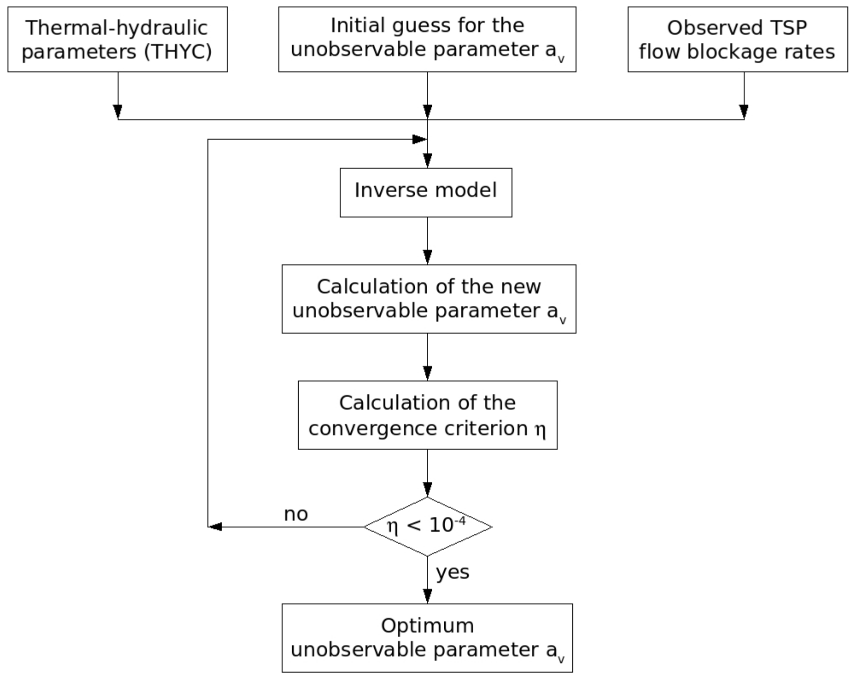

Figure 4: Inverse method for estimation of the unobservable parameter a_v

7 Results

7.1 Estimation of the unobservable parameter

For each size of particles and from the initial guess a_v=10^{-3}, the inverse problem is solved until the convergence criterion becomes less than 10^{-4}. The convergence graphs of the unobservable parameter a_v are shown in Figure 5 according to the size of particles. The inverse method converges after 15 iterations for each size of particles and allows one to evaluate a_v (system (12)).

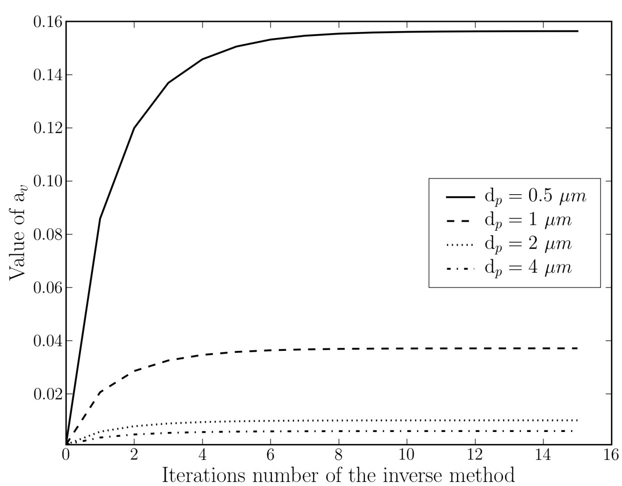

Figure 5: Convergences graphs of the unobservable parameter a_v

$$a_v = \begin{cases} 0.1563 & \text{if } d_p = 0.5\ \mu m \\ 0.0372 & \text{if } d_p = 1\ \mu m \\ 0.0101 & \text{if } d_p = 2\ \mu m \\ 0.0061 & \text{if } d_p = 4\ \mu m \end{cases} \tag{12}$$

Different other sizes of particles have been tested : 0.1 μm, 5 μm and 10 μm. The unobservable parameters for these sizes were respectively equal to 5.3072, 0.0073 and 0.1414. These two last values obtained for the sizes of particles 5 μm and 10 μm do not allow to obtain results of the direct deposit simulation in agreement with observed data. Indeed the vena contracta deposit mechanism is not appropriate for big particles. They are therefore not taken into account in this article.

7.2 Direct deposit simulation

The unobservable parameter a_v is now supposed to be known (12) and a direct deposit simulation for each size of particles is performed over a period of 22 years. This period corresponds to the working period of the considered SG before TV Inspections. The calculated profiles of mean TSP blockage rates after 22 years are presented in Figure 6.

For each leg, the fitted mechanism of vena contracta allows one to obtain the same calculated profiles whatever the size of particles. The inverse method is not sensitive to variations in size of particles included between 0.5 μm and 4 μm. It manages to calibrate the correlation of vena contracta for each size of particles in order to reach the observed data.

The fitted mechanism allows one to obtain two dominant trends for the TSP blockage in SGs. The blockage rate of each TSP is firstly more important on the hot leg than on the cold leg. It is secondly more important at the top than at the bottom of the SG. The mean blockage rate calculated at the upper TSP (TSP number 8) in hot leg is similar to observed data : the results differ only by 3 %. The limit of this deposit model is essentially to overestimate the blockage rate at the upper TSP in cold leg : the results differ by 10 %.

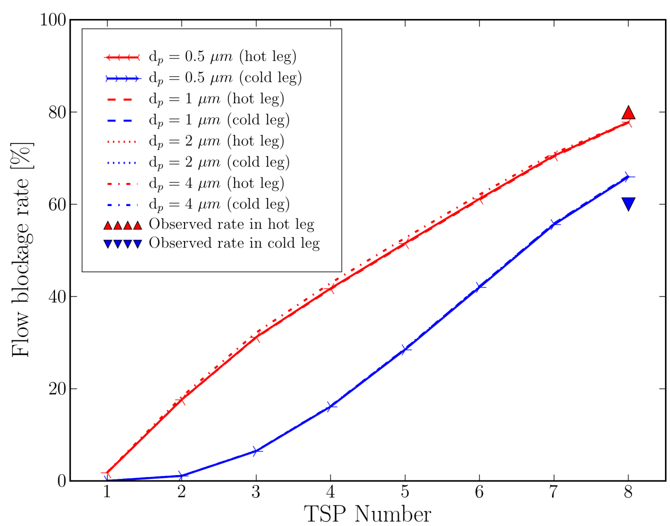

Figure 6: Profiles of mean TSP blockage rates with the optimum value of a_v

Observed and calculated TSP flow blockage rates at the upper TSP are compared in Figure 7 only at the locations where TV Inspections were performed. The relative error between these two distributions is shown in Figure 8. The relative error is lower than 15 % for 63.3 % of calculated TSP flow blockage rates, lower than 30 % for 90.8 % of them and it is higher than 30 % only for 9.2 % of them. The most important differences come mainly from the cold leg where the TSP flow blockage rates are overestimated. In the hot leg they are globally lower than 30 % except for a few control volumes.

One of the limits of the deposit model is that the calculated TSP flow blockage distributions are necessarily symmetrical with respect to the axis perpendicular to the tube lane (horizontal axis). Indeed the deposit mechanisms depend on thermal-hydraulic parameters which are symmetrical with respect to this axis according to calculations. TV Inspections however show that the TSP flow blockage distributions are not symmetrical for the considered SG. One solution to make the deposit model non symmetrical could be to take into account tube plugging which have an impact on thermal-hydraulic parameters. Asymmetry could also be due to swirl imparted by the primary separators.

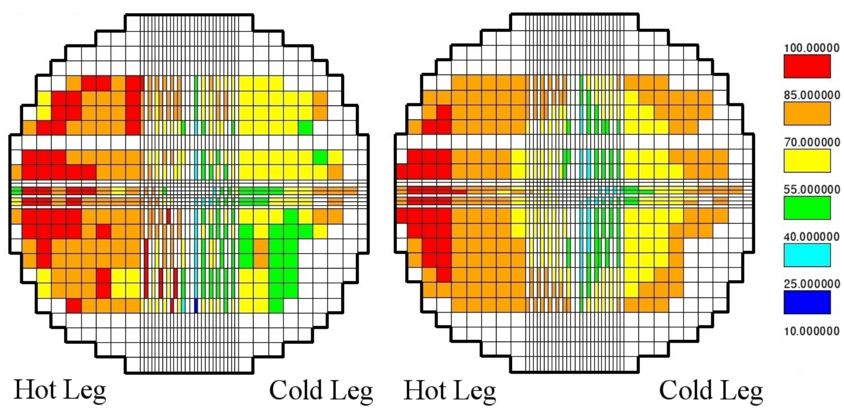

Figure 7: Comparison between observed (left side) and calculated (right side) TSP flow blockage rates at the upper TSP

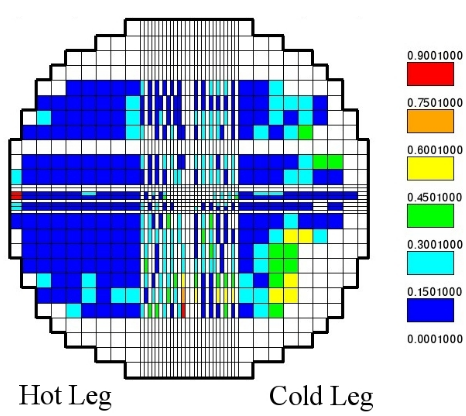

Figure 8: Relative error between observed and calculated TSP flow blockage rates at the upper TSP

The local flow blockage rates obtained for all the TSPs of the SG under study are presented in Figure 9. This calculation seems interesting because the distribution of calculated blockage rates at the upper TSP has the special feature to be more important at the periphery than at the center. This result is in agreement with observed data in certain nuclear plants.

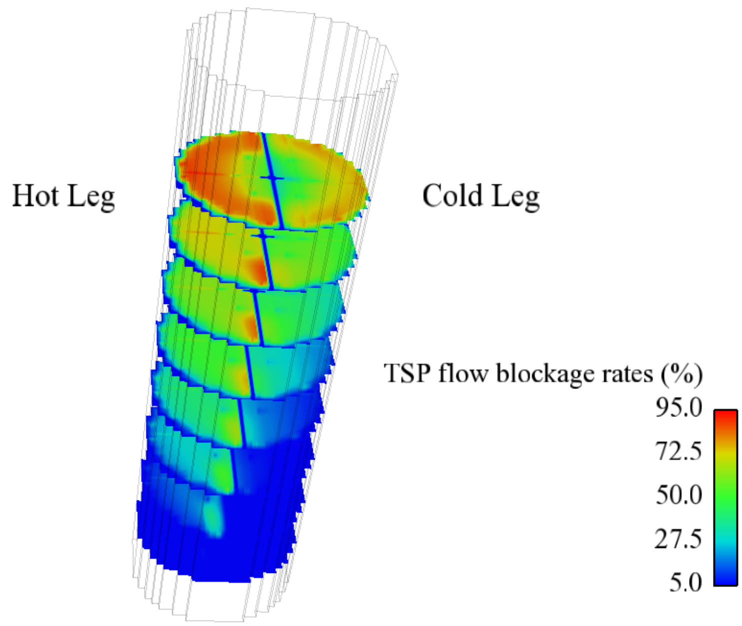

Figure 9: Distribution of calculated TSP flow blockage rates from TSP number 1 to 8

8 Conclusions

Tube fouling and TSP flow blockage in nuclear power plants are a major concern for EDF and motivate the R&D Division to implement a model for the growth of solid deposits on the secondary side of SGs in the EDF thermal-hydraulic code THYC. The aim of this model is to predict the localization and the growth rate of deposits in order to simulate tube fouling, as well as TSP foils clogging leading to secondary flow blockages. The deposit model for tube fouling is based on classical mass transfer correlations. A new correlation called "vena contracta" for TSP flow blockage depending on an unobservable parameter which needs to be tuned from the plants experience has been implemented. The inverse method is able to evaluate this unobservable parameter in PWR conditions, by fitting the results of the THYC simulations to the actual levels of TSP blockage observed in some nuclear plants.

The results obtained in this paper underline two dominant trends for the TSP blockage in SGs : the blockage rate is more important on the hot leg than on the cold leg and at the top than at the bottom of the SG. The TSP blockage rates at the upper TSP has the special feature to be more important at the periphery. The main limit of the model is the symmetrical profile at each TSP. Taking into account tube plugging, or swirl imparted by the primary separators, or even statistical models could be help to solve this problem.

Future work could be performed on the deposit model by making it more complex. For instance, soluble species or the phenomena of removal or strengthening could be taken into account.

Nomenclature

Latin

a_v	Unobservable parameter	[-]
C	Quality	[-]
d_p	Diameter of particles	$[m]$
$\mathbf{J_h}$	Diffusive term of species h	$[kg/m^2/s]$
K_δ	Deposition rate constant	$[m/s]$
k_v	Variable clogging rate	$[1/m]$
m_δ	Deposited mass	$[kg/m^2]$
t	Time	$[s]$
$\mathbf{U_l}$	Liquid average velocity	$[m/s]$
U_z	Vertical mixture velocity	$[m/s]$
V_c	Clogging volume in one foil	$[m^3]$

Superscript

j	Control volume number

Greek

ϵ	Fluid porosity	[-]
Φ	Flow of materials	$[kg/m^2/s]$
Γ	Mass fraction in liquid	$[kg/kg]$
η	Convergence criterion	[-]
μ	Dynamic viscosity	$[kg/m/s]$
ρ	Density	$[kg/m^3]$

Subscript

c	Clogging deposit
δ	Deposition
f	Fouling
g	Vapour
l	Liquid
m	Mixture
p	Particle
r	Removal
s	Soluble species

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