SENSITIVITY ANALYSIS FOR THE CPA-FRONT MODEL, APLICATION TO A GENERIC CANDU 6

Gabriela RADU[1], Ilie PRISECARU[2]

This paper presents a study of the behavior of the flame front following a severe accident in a generic CANDU 6 station containment. The calculations are carried out using the ASTECv2.0r2p2 code with CPA-Front model. The aim is to investigate the influence of the variation of the input parameters for the flame front model with respect to pressure and temperature histories in different containment locations.

Keywords: flame front, severe accident, Latin Hypercube Sampling

1. Introduction

Under severe accident conditions in nuclear power plants, large amounts of hydrogen can be released. This could potentially lead to the formation of flammable mixtures of hydrogen/air/steam in reactor containments. Combustion of these mixtures could lead to pressure and temperature levels that may jeopardize the containment integrity. Hydrogen combustion can cause containment building failure by static or quasi-static pressure loads or dynamic pressure loads, equipment failure due to temperature or pressure effects, and missile generation. The possible consequences depend on the regime of combustion.

Therefore accurate and reliable simulation of combustion is an important task in the analysis of accidents in nuclear power plants. The calculation of all features of hydrogen combustion requires detailed models including the phenomena of turbulent flow, laminar and turbulent deflagration, turbulent flame acceleration, deflagration to detonation transition, and detonation. For best estimate calculations the use of advanced CFD codes with combustion models is recommended. In the frame of integral calculations of severe accidents the application of these codes is too complex and time consuming. Because of the importance of the consequences to reactor safety an adequate estimation of the essential parameters of hydrogen combustion is required inside of the integral codes. To model the hydrogen combustion, the lumped parameter codes use different approaches based on correlations to calculate flame velocity and then

[1] Eng., Institute for Nuclear Research, Pitesti, Romania
[2] Prof., Power Engineering Faculty, University POLITEHNICA of Bucharest, Romania, e-mail: prisec@gmail.com

deduce the amount of burned hydrogen and pressure build up. The main differences refer to the used correlation for predict laminar and turbulent flame speeds [1].

The results of the post-calculations of experiments with flame front model of ASTECv20r2 code have shown that different experiments require different set of model parameters to fit the experimental data best [2]. The selected experiments for these calculations had been carried out in four facilities: THAI, ENACECCEF, Battelle model containment and HDR-containment. Thus, it was not possible to find one fixed combination of model parameters for all situations including for applications in a containment of a real plant [2].

This paper presents a study of the behavior of the flame front following a severe accident initiated by a SBO in a generic CANDU 6 station containment. The calculations are carried out using the CPA-FRONT model of the code ASTECv2.0r2p2. The aim is to investigate the influence of the variation of some input parameters for the flame front model with respect to pressure and temperature histories in different containment locations. For this purpose, an uncertainty and sensitivity analysis for the FRONT model is performed with the coupled codes SUNSET/ASTEC.

2. Model description

The CPA-FRONT combustion model calculates the flame propagation from a containment room into adjacent ones [1], [2]. In the CPA-FRONT model, the flame propagation is modeled inside the junctions. The H_2 combustion takes place in the zones. The burning velocity inside the zones is determined by the flame front velocity calculated by FRONT. The flame front velocity is calculated as the sum of the gas velocity in the junction, V_g, and the turbulent burning velocity, V_t:

$$V_{flame} = V_t + V_g \tag{1}$$

The model uses experimental correlations for the calculation of the flame front velocity.

For the calculation of the turbulent burning velocity, the FRONT model uses the Peters correlation [1], [2]:

$$V_t = V_l (1 + \sigma) \tag{2}$$

with

$$\sigma^2 + 0.39 \frac{l}{l_f} \sigma - 0.78 \frac{u' l}{V_l l_f} = 0 . \tag{3}$$

l is the maximal eddy length in the junction and l_f the laminar flame thickness that follows from the molecular diffusion coefficient $D = l_f V_l$. The laminar flame front velocity V_l is calculated based on the Liu-MacFarlane correlation [1], [2]:

$$V_l = BT^K \exp\left(Lx_{H_2O}\right)\left(\frac{P}{P_{ref}}\right)^{0.2} \tag{4}$$

with B, K, L constants, T the gas phase zone temperature, P the zone pressure, P_{ref} a reference pressure, x_{H_2O} the volumetric fraction of steam. For the turbulence intensity u', the following correlation based on Reynolds number is used [1], [2]:

$$u' = CV_g \operatorname{Re}^n \tag{5}$$

with C and n constants with values estimated on the basis of small scaled experiments. V_g is the gas velocity in the junction and Re the Reynolds number.

3. Flame front behavior, sensitivity analysis

The aim of this study is the application of the flame front model to CANDU 6 containment and the investigation of the influence of some varied input parameters for the model into the variation of the pressure and temperature in different containment zones. The nodalisation scheme of the containment is shown in Fig. 1.

For this evaluation, the containment was represented by a small number of control volumes (zones) connected by junctions. Each control volume includes a containment room or combinations of containment rooms. The flow paths between connected control volumes are constantly open or closed by doors or blow out panels that may open when a pressure difference is exceeded. 95 heat structures are simulated to represent the prestressed concrete walls of the containment structure, reinforced concrete walls of the internal structure of the containment and reactor vault and other steel structures.

The situation investigated is a Station Black-Out scenario with an assumed unavailability of several critical safety systems, which can lead to severe core damage [5]. The transfers of water, steam and hydrogen into the ‘sgr’ zone (SG room) were derived from external sources [5], [6], [7] and used in table forms as input for the flame front calculations. It was assumed that there are sources of ignition in the containment.

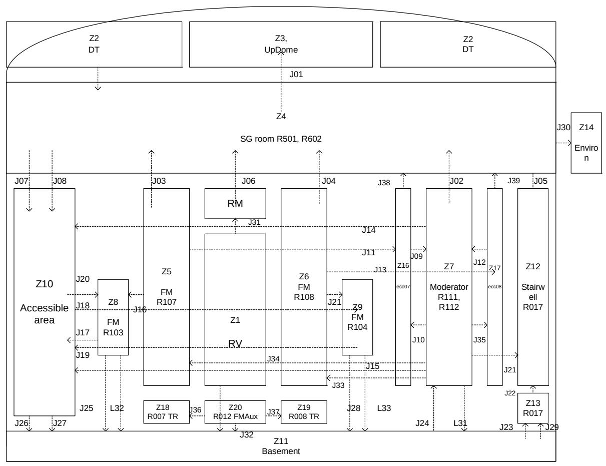

Fig. 1. Nodalisation of the generic CANDU 6 containment

The calculated case is: SBO with recovery; after the recovery of the electric power, the local air coolers have been activated, the all other systems remained unavailable; the hydrogen ignition started in the fueling machine room R107.

In order to study how the variation of the model input parameters influences the important quantities (pressure and temperature histories in different selected locations) in the containment of a real plant represented by a small number of control volumes, a statistical uncertainty and sensitivity analysis for the flame front model was performed. This analysis was carried out using the SUNSET/ASTEC tool [4]. The statistical sensitivity analysis technique used to study the behavior of the CPA-FRONT model is the multiple regression method. The sensitivity measurements (correlation coefficients, regression coefficients, determination coefficients) are calculated to identify which input variables are significant and to quantify their impact. The sensitivity measurements are conditional to the supposed relation between the independent variables and dependent variable.

The influences of following physical quantities are investigated: the turbulent fluctuation velocity, the decay of the turbulence when the flame enters a new volume, and the turbulence length (vertical and horizontal). It was assumed that these parameters of the CPA-FRONT model, or factors, vary uniform with values in the ranges derived from the post-calculations with the model [1], [2], [3]. Table 1 below presents the model parameters investigated and their ranges.

It was considered two values for the constant *n* in the equation (5): -0.12 if the constant $C>0.9$, and -0.119 if $C<0.9$ (on the basis of values used in the post-calculations of the experiments). The values for Liu-McFarlane are taken from the zone with larger hydrogen concentration, but with the initial temperature of the accordant zone.

Table 1

CPA-FRONT model parameters considered in the uncertainty and sensitivity analysis

Factor	Parameter CPA-FRONT model	Description	Range Investigated
x1	Turbulence intensity	C constant in the equation (5) of the turbulent fluctuation velocity u'	0.042÷1.7, selected on the basis of the values used in the investigations of the experiments with the FRONT model.
x2	Turbulence decay coeficient	The decay of the turbulence when the flame enters a new volume	0.2÷1.0, selected on the basis of the values used in the post-calculations of experiments
x3	Turbulence length in horizontal direction	Turbulence length for horizontal junctions (in the Peters correlation – (3))	0.0÷1.0, selected on the basis of the values used in the post-calculations of experiments
x4	Turbulence length in vertical direction	Turbulence length for vertical junctions (l minim in the Peters correlation –(3))	0.001÷0.0125, selected on the basis of the values used in the post-calculations

These parameters were sampled randomly using LHS (Latin Hypercube Sampling) method. For this case, 100 samples of each parameter selected were taken by this method and used to form 100 ASTEC analyses of the accident. The results of these calculations constitute samples of the distribution of interest results. The calculations are carried out for 40000s from the 9128 second of the accident and it was studied the relation between the selected model parameters (independent factors) and the following response variables: pressure and temperature in the selected control volumes, the duration of the combustion and the ignition time. The distributions of the pressure and of the temperature at the combustion time are given in the figures 2 and 3.

The regression model is used to obtain global sensitivity measures of the effect of the factors X (x_1, x_2, x_3, x_4) variations on the variations of the dependent variables Y ($T_{gas-sgr}$, P_{sgr}, $T_{gas-fmr107}$, P_{fmr107}, DSG, DFM, T_{comb}). Figures 4, 5, 6, and 7 present these sensitivity measurements for the temperature and the pressure at the combustion time (peak values) and at 40000s, combustion duration in ‘fmr107’ and ‘sgr’ zones and the ignition time.

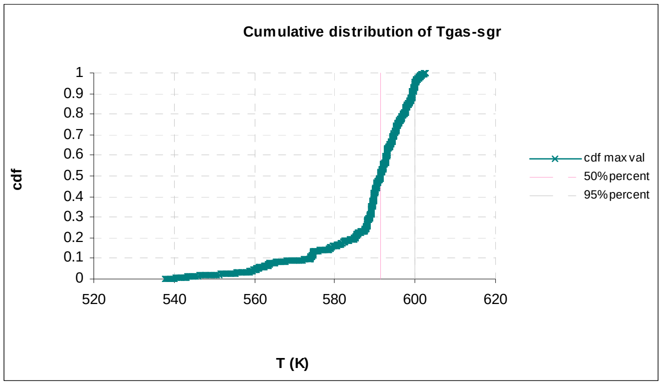

Fig. 2 Cumulative distribution function of the gas temperature (peak value) in the 'sgr' zone where the flame is propagated

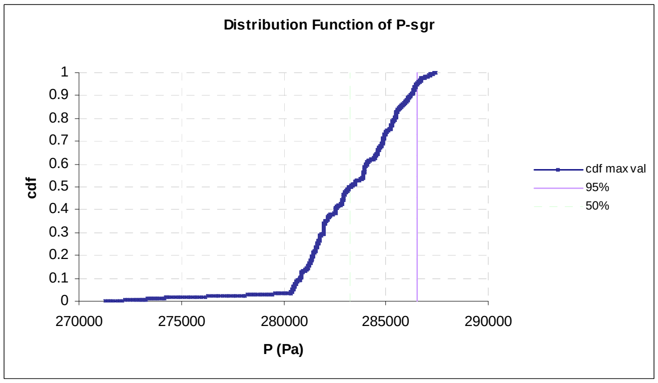

Fig. 3 Cumulative distribution function of the pressure (peak value) in the 'sgr' zone

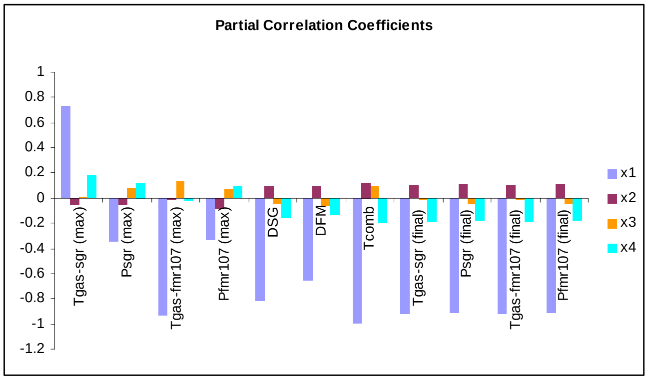

Fig. 4 Partial correlation coefficients between X_i and the response Y in the multi-linear model

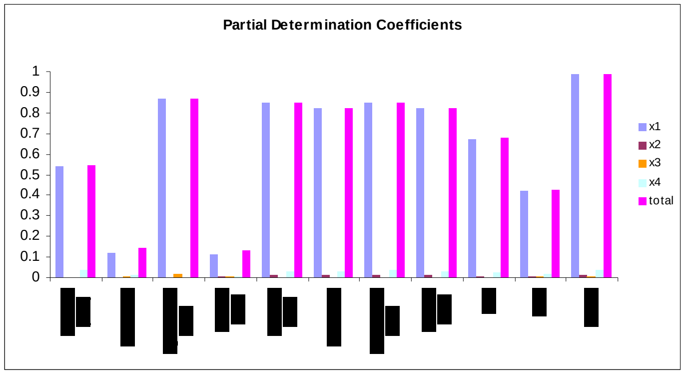

Fig. 5 Coefficients of partial determination associated with x_i in the multi-linear model

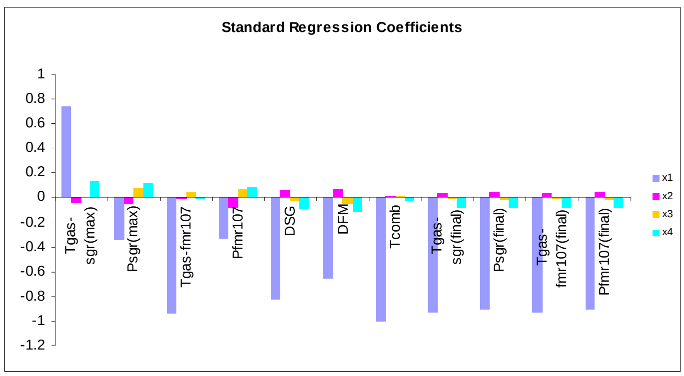

Fig. 6 Standardized regression coefficients for the dependent variables Y

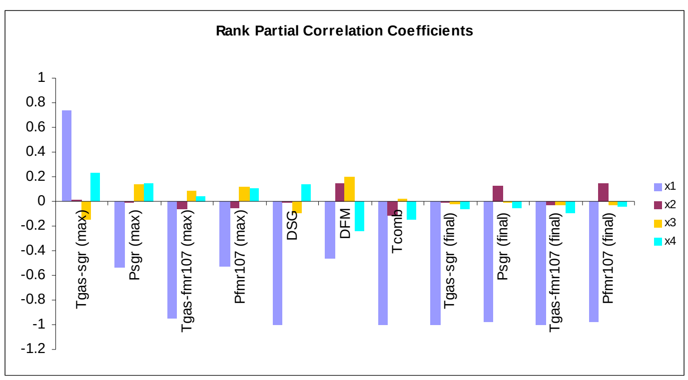

Fig. 7 Rank partial correlation coefficients between X_i and the response Y in the isotonic model

The quality of the regression model is mostly quantified by the value of the coefficient of determination. This coefficient measures the explanatory ability of a model. In the case of the variable $T_{gas\text{-}sgr}$, representing the peak temperature inside the 'sgr' zone, the linear model explains 54.4% of the $T_{gas-sgr}$ variations. The coefficients of partial determination show that $T_{gas-sgr}$ variability is due at 54.1% to the turbulence intensity variation. For the output variables P_{sgr} and $P_{fmr107,}$ (the pressures at the combustion time), it can see, from the values of the coefficient of determination, that neither the linear nor the monotonous relation fit. For the temperature peak in the 'fmr107' zone, the coefficient of determination is near 0.9 for the monotonic based analysis so that it is concluded that there is some monotonic relation between inputs and outputs. For the combustion duration inside the 'sgr' zone and for ignition time, the coefficient of determination for the monotonic based analysis is near to 1.

4. Conclusions

This paper presents some of the results of a statistic uncertainty and sensitivity analysis for the FRONT model. The aim of this calculation was the application of the flame front model to CANDU 6 and the investigation of the influences of the variation of the input parameters for the model into the important responses in a real plant containment represented by a small number of control volumes. The multiple regression model was used to obtain global sensitivity measurements of the effect of the input parameter variations on the variation of output. The case studied corresponds to a scenario during which the gas mixture is close to the flammability limit. For this case study, the main influence on the results is brought in by the variations of the turbulence intensity. The all other input parameters have small influences.

R E F E R E N C E S

[1]. *** ISP-49 on Hydrogen Combustion, NEA/CSNI/R(2011)9, 18 Jan 2012
[2]. *J. Eckel, W. Erdmann*, **"**The ASTEC flame FRONT module, Model description and parameter studies", **rev. 1**, ASTECV2/DOC/12-02, ECK-TN-01/11 RS1190 RS 1185, July 2012.
[3]. *I. Kljenak, R. Connes*, "Simulation of Hydrogen Combustion Experiment THAI HD-22", ASTEC Users' Club Meeting, Aix-en-Provence, France, January 29th – February 1st, 2013
[4]. ***ASTEC/SUNSET User Guidelines, CS-SI, DPAM-SEMIC-20011-100, ASTEC-V2/DOC/1102, December 2011
[5]. *S.M. Petoukhov, P.M. Mathew*, "Status of MAAP4-CANDU code development and simulations of severe core damage accidents for a generic CANDU 6 plant", Technical Meeting on Severe Accident and Accident Management Toranomon Pastoral, Minato-ku, Tokyo, Japan, March, 2006.
[6]. *Soo-Yong Park,*, Kwang-Il Ahn*, "Comparative analysis of Station Blackout Accident progression in typical PWR BWR, and PHWR", Nuclear Engineering and Technology, **vol.44**, no.3 April 2012
[7]. *M. Mathew*, „IAEA Meeting on Preparatory Review of Accident Management", Bucharest, February 2007.