Collection de notes internes
de la Direction
des Etudes et Recherches

Production d'énergie (hydraulique, thermique et nucléaire)

ANALYSE THERMOHYDRAULIQUE AVEC LE CODE THYC D'UN CŒUR REP DONT UN ASSEMBLAGE POSSEDE DES GRILLES INTERMEDIAIRES DE MELANGE

THERMAL-HYDRAULIC ANALYSIS OF PWR CORE INCLUDING INTERMEDIATE FLOW MIXERS WITH THE THYC CODE

97NB00103

EDF
Electricité de France

DIRECTION DES ÉTUDES ET RECHERCHES
SERVICE RÉACTEURS NUCLÉAIRES ET ECHANGEURS
DÉPARTEMENT TRANSFERTS THERMIQUES ET AÉRODYNAMIQUE

EDF
Electricité de France

Juillet 1997

MUR J.
MEIGNIN J.C.

ANALYSE THERMOHYDRAULIQUE AVEC LE CODE THYC D'UN CŒUR REP DONT UN ASSEMBLAGE POSSEDE DES GRILLES INTERMEDIAIRES DE MELANGE

THERMAL-HYDRAULIC ANALYSIS OF PWR CORE INCLUDING INTERMEDIATE FLOW MIXERS WITH THE THYC CODE

Pages : 10

97NB00103

Diffusion : J.-M. Lecœuvre
EDF-DER
Service IPN. Département PROVAL
1, avenue du Général-de-Gaulle
92141 Clamart Cedex

ISSN 1161-0611

SYNTHÈSE :

La caléfaction est l'une des principales limites de fonctionnement des réacteurs à eau sous pression (REP). La sûreté exige de garantir la non-apparition de ce phénomène lors des conditions de fonctionnement normales ou incidentelles.

EDF a développé son propre outil de simulation numérique, basé sur le code de thermohydraulique THYC, pour ses analyses en flux critique. Il permet à EDF d'évaluer de façon indépendante les performances des combustibles et les marges de sûreté.

Dans cette note, les trois principaux aspects de l'analyse en flux critique sont évoqués. Il s'agit de :

- l'utilisation d'un code de thermohydraulique validé. On donne une description du code de thermohydraulique THYC développé à EDF. Le code est particulièrement adapté au calcul des transferts de masse et d'énergie dans les composants nucléaires. Il repose sur une modélisation tridimensionnelle de l'écoulement par une approche de type milieu poreux. EDF a mis en place un important programme de validation du code. On présente ici plus particulièrement les expériences AGATE grilles décalées et GRAZIELLA prélèvements réalisées au CEA ;

- la prédiction efficace du flux critique. Le flux critique est prédit à partir des grandeurs thermohydrauliques locales telles que la pression, la vitesse massique et le titre enthalpique. Le code THYC est utilisé d'une part pour la prédiction du flux critique à l'aide de corrélations qui sont la propriété des fournisseurs, d'autre part pour l'élaboration de nouvelles corrélations. Un prédicteur de flux critique a notamment été construit à partir de 570 points expérimentaux de flux critique issus de la banque de données de l'EPRI ;

- une méthodologie de modélisation et de calcul applicable aux études de conception thermohydraulique des cœurs. Une méthodologie en trois étapes a été développée pour les calculs de conception standard. Les cœurs mixtes, dont certains assemblages sont équipés de grilles intermédiaires de mélange (GIM), présentent une configuration pour laquelle l'approche thermohydraulique standard, basée sur l'analyse par sous-canaux, n'est pas adaptée. L'application de THYC à ce problème montre comment le modèle réellement tridimensionnel permet de représenter les pertes de charges supplémentaires dues aux GIM.

Abs :

EXECUTIVE SUMMARY :

Departure from nucleate boiling (DNB) is one of the major limiting factors of pressurized water reactors (PWRs). Safety requires that occurrence of DNB should be precluded under normal or incidental operating conditions.

EDF has developed its own numericl tool based on the thermal-hydraulic THYC code in order to perform DNB analysis. This provides EDF with an alternative and independent way of evaluating fuel performances and safety margins.

~~In this paper,~~ The three main aspects of DNB thermal-hydraulic analysis are discussed. ~~This includes~~ :

- use of a validated thermal-hydraulics code. The thermal-hydraulic THYC code developed by EDF is described. The code is devoted to heat and mass transfer in nuclear components. A fully three-dimensional representation of the flow is proposed in conjunction with a porous-body approach. An extensive validation program has been set up for the code. Special attention is focused on the CEA AGATE-partial grids experiment and the CEA GRAZIELLA-P subchannel sampling experiment ;

- an efficient way of predicting critical heat flux. Critical Heat Flux (CHF) is predicted from local thermal-hydraulic parameters such as pressure, mass flow rate, and quality. CHF predictions with THYC come in two ways : use of CHF correlations supplied by fuel vendors or derivation of CHF predictors. In particular, a predictor has been built from 570 CHF experimental data points taken from the EPRI compilation ;

- a core representation and calculation methodology that can be applied to core design. A three stage methodology to evaluate thermal margins ~~has been set up~~ in order to perform standard core design, is described. The problem of mixed cores, where some of the fuel assemblies have intermediate flow mixers (IFMs), is an area where the standard approach to thermal-hydraulics based on subchannel codes is not very appropriate because of significant cross flows. Application to THYC to this problem shows how its fully three-dimensional model can represent changes in pressure drops because of IFMs.

PWR TYPE REACTORS

HYDRAULICS

DEPARTURE NUCLEATE BOILING

T CODES

MASS TRANSFER

HEAT TRANSFER

CRITICAL HEAT FLUX

REACTOR CORES

E 3200

97NB00103

THERMAL-HYDRAULIC ANALYSIS OF PWR CORE INCLUDING INTERMEDIATE FLOW MIXERS WITH THE THYC CODE

J. Mur
Electricité de France - DER
6 quai Watier
78401 Chatou, France
fax: +33 1 30 87 79 49
e-mail: jerome.mur@der.edf.fr

J.-C. Meignin
Electricité de France - SEPTEN
12/14 avenue Dutrievoz
69628 Villeurbanne, France
fax: +33 4 72 82 77 09

I. THE THYC CODE

THYC[1] is a thermal-hydraulic code developed by 'Électricité de France' (EDF). Its application scope is single or two-phase flow in rod bundles. It is especially devoted to heat and mass transfer in the following nuclear components : reactor cores, steam generators and condensers. The code differs from subchannel analyses which assume a prevailing axial component of velocity and uniform pressure at each elevation. Here, a fully three-dimensional representation of the flow is proposed in conjunction with a porous-body approach.

This paper will be restricted to PWR core analysis. Mixed cores, steam line break analysis, rod ejection represent cases where the need for a 3D code is necessary for improved determination of local flow conditions. Excessive conservatism can also be removed by a more realistic approach to flow conditions. The two next sections provide basic information on the model and on the code environment.

A. The THYC model

The code is really three-dimensional. No direction receives special treatment as opposed to conventional subchannel codes that assume small diversion cross flows with respect to the axial velocity. THYC being originally devised as a 3D code, boundary condition can be imposed in a three-dimensional way with no restriction. The numerical scheme being based on finite volumes, conservation of mass and energy is verified.

The liquid-vapor flow is described by three equations that respect strict conservation of mass, momentum and energy. An additional equation can be implemented into the model in order to allow thermodynamic non-equilibrium between the vapor and the liquid phase (subcooled boiling or super-heated steam). This set of averaged equations is completed by closure relationships. The main correlations available from literature are implemented in the THYC code.

B. Code environment

The THYC code has been developed under a Quality Assurance program. In practice, this means :
– a comprehensive and detailed 4-volume documentation (modeling and numerical scheme, programming, validation and user's manual including pre- and post-processing)

– identified releases (latest release : THYC 3.2) where new options are included and errors detected in the previous release are corrected
– a so-called "user's club" where new applications of the code are presented on a regular basis.

Gains in engineering productivity have been attained by easy pre-processing. In this respect, for core calculations and DNB test evaluation, the THYCOX pre-processor can be used. Technological data (e.g. core geometry, fuel assembly description) are indicated in a very simple manner as well as numerical parameters. Meshing and T/H parameters such as flow areas, hydraulic diameters are then automatically calculated for each type of mesh, so that calculations can be started very rapidly.

The code is also coherent with other numerical tools developed by EDF. Simultaneous calculation of T/H and neutronics in a reactor core is thus made possible by code coupling. The code coupling tool CALCIUM[2] manages real-time information exchanges so that the THYC code can be used interactively with the COCCINELLE[3,4] code for neutronics.

II. VALIDATION PROGRAM

PWR core thermal-hydraulic analysis requires computation of accurate local coolant flow conditions. EDF has set up an extensive validation program for the THYC code. A parallel program is also underway for steam generators where another range of T/H conditions in terms of void fraction, pressure and mass flow rate is investigated.

The number of experiments retained in the THYC-core validation program is quite large. Data have been collected from various facilities (Columbia University, CEA, EDF, ...). These experiments are listed in Table 1. They fall into three categories :

– analytical experiments. Thermal-hydraulics in rod bundles is studied for simple geometrical configurations (grids are without mixing vanes) in order to validate basic closure relationships.

Table 1: THYC validation program (* not achieved yet)

Experimental loop	R&D facility source	Main features	Mock-up (rods)	Fluid	Measurement
COLUMBIA Thermal experiments	Columbia University	Thermal non-equilibrium	9x9	water	temperature
GE9	General Electric	adiabatic flow in a 3x3 bundle	3x3	water air	void fraction
VATICAN	EDF	heated bundle with structure grids	10x4	freon	temperature, void fraction pressure drop
EDGAR	EDF	velocity field beyond a mixing grid in air	5x5	air	LDV velocity concentration
VATICAN-2	EDF	heated bundle with mixing grids	10x4	water / freon	LDV velocity, temperature void fraction, pressure drop
HYDROMEL	CEA Grenoble	tracer sampling	5x5	water	concentration
AGATE	CEA Grenoble	velocity field beyond a mixing grid	5x5	water	LDV velocity
GRAZIELLA-P	CEA Grenoble	subchannel sampling	5x5	freon	quality, mass flow rate
VATICAN-3 *	EDF	partial grids in heating zones	10x4	water / freon	LDV velocity, temperature void fraction, pressure drop
AGATE-2	CEA Grenoble	velocity field around a partial grid	5x5	water	LDV velocity
HERMES-RECETTE	CEA Cadarache	interface of different fuel assemblies	34x17	water	LDV velocity
HERMES-THROMBOSE *	CEA Cadarache	assemblies with different inlet flow	34x17	water	LDV velocity

– mixing effects induced by mixing vanes downstream of a grid. These effects have a strong impact on CHF values. In particular, the impact of different mixing vane layouts can be investigated.

– long range 3D effects. Being able to predict cross flows induced by grids with different pressure drop coefficients is a major concern for EDF. A program is currently under way and deals with three-dimensional configurations that are close to mixed cores or inlet maldistribution problems.

In this paper, special attention is focused on the CEA AGATE test loop. The test section consists of a 5 by 5 rod bundle. Two halves of a structure grid are placed at different elevations in order to create a chicane effect. In Figure 1, calculated transverse velocities through a rod-to-rod gap in the center of the bundle are compared to LDV measurements.

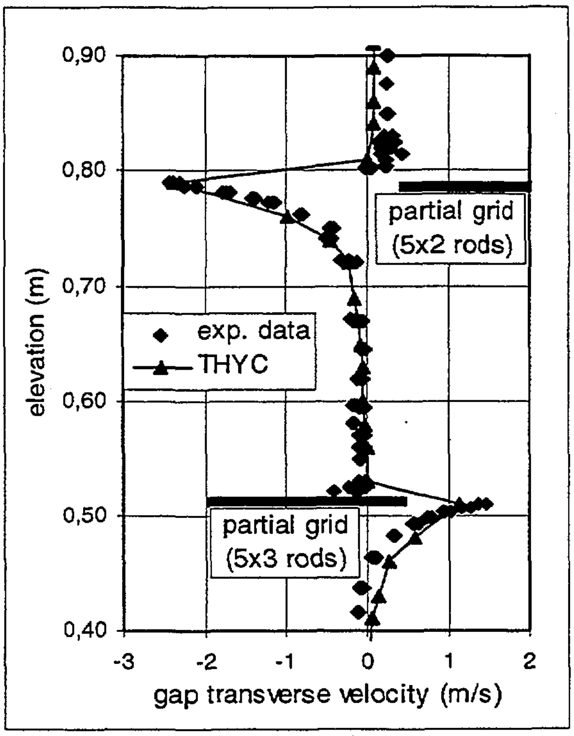

Figure 1: Measured vs. predicted transverse velocity, AGATE test section with partial grids.

The CEA GRAZIELLA–P[5] subchannel sampling experiment is also of great interest for code validation. This experiment gives access to subchannel mean values of mass flow rate and quality that can be directly compared with code predictions. Several maps of the flow at the outlet of a 5 by 5 heated rod bundle could be drawn from experimental results for a wide range of outlet qualities. Results of a simulation with the standard THYC model are plotted against experimental data in Figure 2.

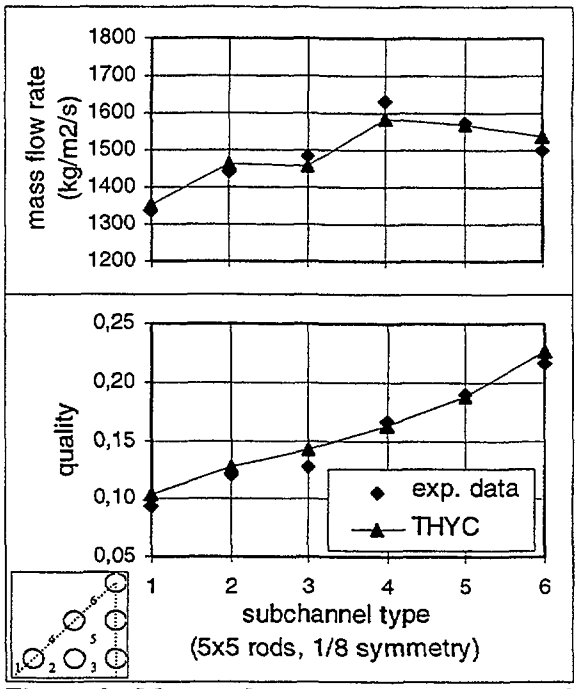

Figure 2: Measured vs. predicted subchannel mean values of mass flow rate and quality, GRAZIELLA–P test section.

III. CHF PREDICTIONS WITH THYC

This section deals with the ability of the THYC code to predict CHF from local thermal-hydraulic parameters such as pressure, mass flow rate, and quality. CHF predictions with THYC come in two ways : use of CHF correlations supplied by fuel vendors or derivation of CHF predictors.

A. Use of correlations

Many CHF correlations that are usually fuel vendors proprietary have been tested with THYC. Therefore, the tool 'THYC + Correlation X' can be given statistical information on the P/M distribution (P = Predicted heat flux, M = Actual heat flux). By analyzing CHF data, a safety design criterion has been computed for the main CHF correlations. The objective here is to verify with an independent code the range of validity of these correlations. Most of them being fuel vendor proprietary, they do not appear in the standard THYC release.

B. Derivation of a CHF predictor

An alternative approach to CHF predictions is to develop our own predictors. CHF predictors are obtained by correlating local T/H parameters (pressure, mass flow rate, quality) to the actual heat flux M. A statistical method is needed to perform this task. DNB being a complex phenomenon, a flexible and efficient numerical software developed by the French Atomic Energy Commission (CEA) has been chosen : the Pseudo-Cubic Spline Method (PCSM)[6]. The predictor is determined by minimizing a certain energy and using multidimensional cubic spline functions.

The two objectives of interest for EDF are :
- fuel performance comparison,
- more reliable knowledge of safety margins.

In particular, a predictor has been built from CHF experimental data taken from the EPRI compilation. Eight data banks, that include 570 data points, have been investigated[7]. Three flow parameters are used : local pressure, mass velocity and quality, calculated by THYC with a standard three-equation model. Two geometrical parameters are also explicitly taken into account: heated length and grid spacing. Comparisons have been made with the WRB-1 correlation[8], obtained on the same data bank with local parameters calculated by the THINC code : lower standard deviations of the predicted over measured (P/M) CHF ratio were found for all the data banks analyzed (Table 2).

Table 2: Comparison between THYC+PCSM predictor and the THIC+WRB1 predictor.

	Mean P/M		Standard deviation	$\sigma_{P/M}$ (%)
Data base	THYC + PCSM	THINC + WRB1	THYC + PCSM	THINC + WRB1
E156	0.999	1.004	**6.60**	**8.05**
E157	1.000	1.010	**4.84**	**8.48**
E158	0.997	1.030	**7.73**	**10.48**
E160	1.000	1.050	**5.11**	**10.20**
E161	0.973	0.996	**5.20**	**6.55**
E162	0.975	1.000	**6.21**	**7.96**
E164	1.050	1.002	**6.40**	**8.52**

A 95/95 design criterion based on these results was calculated using Owen's method : it was found equal to 1.13, instead of 1.17 for WRB1. This predictor is now available in the latest THYC version, so that CHF predictions by this predictor are now made possible.

IV. CORE CALCULATIONS

This section describes application of THYC to thermal-hydraulic analysis of PWRs. It is shown how a three-dimensional code like THYC can handle this problem. A methodology to evaluate thermal margins has been set up in order to perform standard core design. Application of THYC to the problem of mixed cores, where some of the fuel assemblies have intermediate flow mixers (IFMs) is also presented. This is an area where the standard approach to thermal-hydraulics based on subchannel codes is not very appropriate because of significant cross flows.

A. Thermal margin analysis

A three-stage methodology has been developed in order to determine the MDNBR (Minimum Departure from Nucleate Boiling Ratio) within the core. Determination of the MDNBR in the hot subchannel is obtained by progressively restricting the computational domain while refining the calculation mesh. The entire procedure is depicted in Figure 3.

Stage 1. Each fuel assembly is represented by a single mesh. It follows that a large scale thermal-hydraulic field is computed within the core. A quarter of a core is normally modeled. In particular, mass, momentum and energy transfers are computed between the hot assembly and neighboring assemblies.

Stage 2. The hot assembly is modeled on a 4-subchannel per mesh basis, so that a standard PWR 17x17 fuel assembly is divided into 9x9 meshes. Transfers of mass, momentum and energy derived from stage 1 results are used as boundary conditions for this calculation. At this stage, mesh-dependent geometrical parameters are calculated (e.g. hydraulic diameter, flow sections, porosity, ...). DNBR calculations are performed and the location that corresponds to the minimum of the DNB ratio is analyzed by the third stage.

Stage 3. The approach used between stages 1 and 2 is applied again. The MDNBR is calculated by a 4x4 mesh once more, so that one mesh represents a fourth of a subchannel.

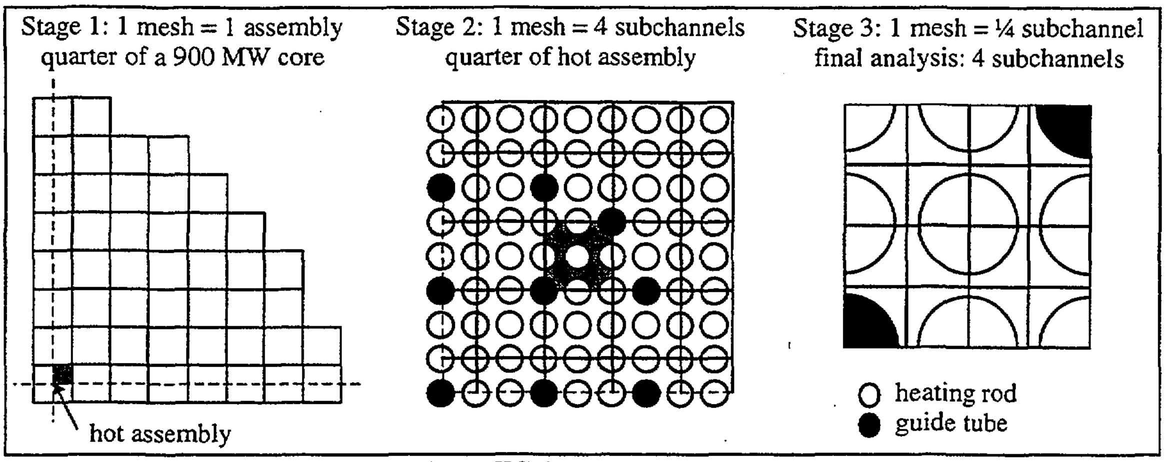

Figure 3: THYC three-stage core analysis.

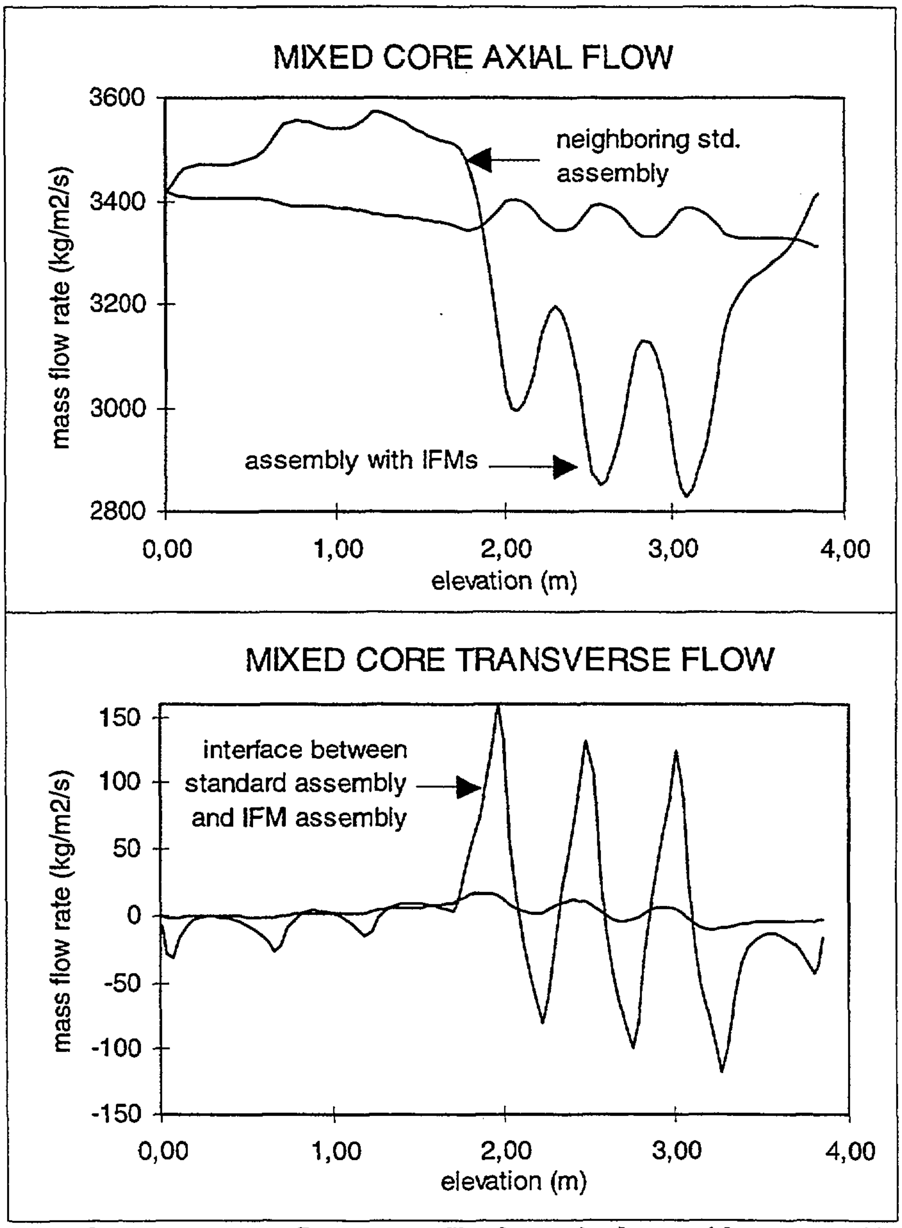

Figure 4: Axial and transverse mass flow rate profiles for a mixed core with one assembly with IFMs.

It has been shown that this approach is conservative in terms of thermal margin analysis. The whole procedure is done automatically from the preprocessor input files. Calculation times are of the order of 2 min. with a typical workstation (HP 9000/735). It is reminded that these computation times are obtained with the THYC code that develops a genuine 3D approach to thermal-hydraulics.

B. Example of 3D calculations

Mixed cores modeling is now a major concern with PWRs. In this example, the impact for the central fuel assembly of three IFMs in the upper part of the bundle have been modeled. An arbitrary 0.5 pressure drop coefficient has been chosen for IFMs. The rest of the core is loaded with standard fuel assemblies, so that cross flows are expected.

The example shown here represents a 900 MW core with 157 fuel assembly under nominal operating conditions with a cosine heat flux.

Results of stage 1 calculations are presented in Figure 4. It can be observed how the code can represent changes in pressure drops because of IFMs. Impact of additional mixing grids clearly appears as well as its effect on neighboring fuel assemblies. Variations in the axial and transverse mass flow rate present how the code reacts to changes in grid pressure drop coefficients. In particular, smooth variations in the axial velocity can only be obtained by a 3D code that computes a genuine 3D pressure field. Most subchannel codes assume uniform pressure at each elevation, so that strong variations of the axial component are obtained just downstream of a partial grid.

CONCLUDING REMARKS

THYC, a 3D thermal-hydraulic code has been developed and is now fully operational for PWR cores. Real 3D thermal analysis is now available, so that studies that involve mixed cores, steam line break or rod ejection accidents can be treated without assumption of prevailing axial velocity as opposed to subchannel codes. The THYC code is based on an extensive validation program. In addition, CHF predictions can be improved by advanced statistical methods and a core computation methodology has been set up. This provides EDF with an alternative and independent thermal-hydraulic code to evaluate safety margins and fuel DNB performances.

REFERENCES

1. C. CAREMOLI, P. RASCLE, S. AUBRY and J. OLIVE, "THYC, a Thermal HYdraulic Code for 3D two-phase flows in tube bundles," Second International Seminar on subchannel Analysis, Electric Power Research Institute, 19th Nov 1993.

2. D. BEAUCOURT, C. CAREMOLI, "CALCIUM, a new tool for codes coupling," CRAY User Group Meeting, Tours, France, 1994

3. J.P. WEST, F. BLANCHON & al., "COCCINELLE : a consistent software for light water reactor physics calculations design, safety, management, monitoring and surveillance," PHYSOR 90, Marseille, France

4. P. TETART, C. HERVOUET, "Pin by pin calculations," Intl. Conf. on Modelling & Simulation for the Nuclear Industry, Glasgow, UK - 1993

5. Ch. CHICHOUX, "Essais de prélèvement avec grilles non mélangeuses GRAZIELLA," rapport CEA D.R.N. STR/LTDF/96-001 - Jan. 1996

6. F. de CRECY, "Pseudo-Cubic thin-plate type Spline Method for analyzing experimental data," NURETH-6 proceedings, Grenoble, France - Oct. 5-8, 1993

7. D. BANNER, S. AUBRY, "CHF predictor derived from a 3D thermal-hydraulic code and an advanced statistical method," Fourth International Topical Meeting on Nuclear Thermal-Hydraulics, Operation and Safety, Taipei, Taiwan - April 5-8, 1994

8. F.E. MOTLEY, "New Westinghouse correlation WRB-1 for predicting Critical Heat Flux in rod bundles with mixing vane grids," WCAP-8763 (Class 3), July 1976