

Teaching Basic Pressurized Water Reactor Core Thermal-Hydraulics Employing Worksheet-Based Exercises*

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The Technical University of Catalonia (UPC) is involved in many initiatives devoted to the examination of new approaches both to teaching organization and to the methodology used. Teaching basic thermal-hydraulic analysis of nuclear plants to students having their first contact with nuclear technology is a challenging activity in Nuclear Departments and Institutes. An important background in computing and numerical algorithms seems to be needed from the very beginning and the student has to understand physical phenomena and aspects of engineering. Traditionally the challenge was apparently solved by only selecting candidates who had a high level in all these skills for nuclear technology studies. This paper explains how, by using a properly organized worksheet, a very limited number of teaching sessions, together with corresponding study on the part of the student, provide interesting results to consolidate knowledge of the most relevant aspects of Pressurized Water Reactor (PWR) core thermal-hydraulics. We do not offer a full description of the tools used, but provide the most relevant aspects and we describe the educational experience of both its development and use. We give some detail of how, from the very beginning, easy calculations are performed by the student using a standard worksheet which enables him or her to concentrate on concepts and parameters related to phenomena and thus on general understanding of the basic overview of the physics involved. All of this is supplemented with simple, but realistic results produced by the student. The worksheet has been tested and is currently being used successfully at the UPC.

Keywords: pedagogy; active learning; educational experience; didactic computing tool; thermalhydraulics of nuclear power plants; heat transfer

INTRODUCTION

THE TECHNICAL UNIVERSITY OF CATALONIA (UPC) is involved in many initiatives devoted to the examination of new approaches both to teaching organization and to the methodology used. Some of them are very general, such as those related to educational organization, while others are more connected with daily lecture preparation. One of the UPC research institutes, the Institute of Education Sciences (ICE), has the general mission of contributing to the enhancement of quality education at UPC by means of promoting improvement and innovation in teaching and learning in higher education and by providing training for academic staff of UPC institutes and departments in new educational resources.

Improvements in engineering teaching can be carried out by following many different pedagogic approaches that could be traditional, active or mixed [1]. At UPC, recent innovation has been

focused mainly on the field of active pedagogies, specially:

- Collaborative/Cooperative Learning [2]
- Problem-Based/Project-Organized Learning
- Semi-Distance Learning [3]
- Web-Based Teaching and Learning
- Web-based Open Learning Environments
- E-Based Educational Materials
- Student Workload and ECTS (European Credit Transfer System) Development.

Thermalhydraulics of Nuclear Power Plants (THNPP) is taught at two different levels at UPC: at degree level as part of the Nuclear Option of Mechanical Engineer and at master level as part of the Master on Energy Engineering. In both cases, the subject is part of a broader course like Nuclear Safety or Accident Analysis and only a limited number of teaching hours are specifically devoted to THNPP (20 at degree level and 40 at master level). There is also the possibility for students to choose a thesis subject related to the field. If they do, learning Thermalhydraulics is assured as they will devote an additional semester to solving an engineering problem, probably

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related to an actual project, with strong interaction with a properly selected advisor. If a student does not choose a thesis subject in the THNPP, it is even more important to use properly the limited time available in order to allow him or her to get the right picture of engineering activities related to THNPP.

The subject of THNPP is basically connected to calculations. Heat transfer within the different systems and components of a nuclear power plant is the main concern of the thermal-hydraulic analysis of nuclear systems and is one of the most relevant subjects a nuclear engineer needs to be familiar with when dealing with NPP (Nuclear Power Plant) technology. Starting at a microscopic level when fission fragments convert their kinetic energy into thermal energy, heat transfer is significant at many different stages. Heat generation and conduction within the fuel pellet, heat transfer through the gap, conduction within the cladding, and convection to the coolant are the main phenomena that take place within the reactor core. Once the coolant extracts the heat from the fuel rods, heat transport to steam generators (in a PWR—Pressurized Water Reactor) is also relevant. Steam production in the secondary side and steam behavior in the turbine or the condenser complete the list of phenomena that take place in systems and components where heat transfer is a significantly observable fact that an engineer must be concerned with.

In the engineering field, “to be concerned with”

very often means to calculate, to figure out, or to quantitatively predict an expected behavior after considering some given boundary conditions.

The significance of thermal-hydraulic analysis can also be confirmed by considering its main goals which are:

- To ensure power extraction during normal and abnormal operation [4]
- To provide necessary feedback for other engineering branches such as neutron-kinetics design [5], material stability, coolant chemistry, fuel mechanics . . .

Thermalhydraulic analysis is an essential part of safety assessment and thus:

- The amount of energy that can be extracted from a given core depends on its results
- Its results are needed to carry out a large number of other engineering tasks.

Thermalhydraulic calculations are not straightforward. They involve parameters with large variation fields and functional dependences that are sometimes not known, such as heat transfer coefficients. The involved phenomena are complex, such as two-phase flow or heat transfer in the vicinity of a boiling crisis. Geometric aspects are also intricate and it is very often difficult to reduce actual components, such as fuel rods or SG (Steam Generator) tube bundles, to one- or two-dimensional models. The correlations used are multi-parametric, often semi-empirical and only quali-

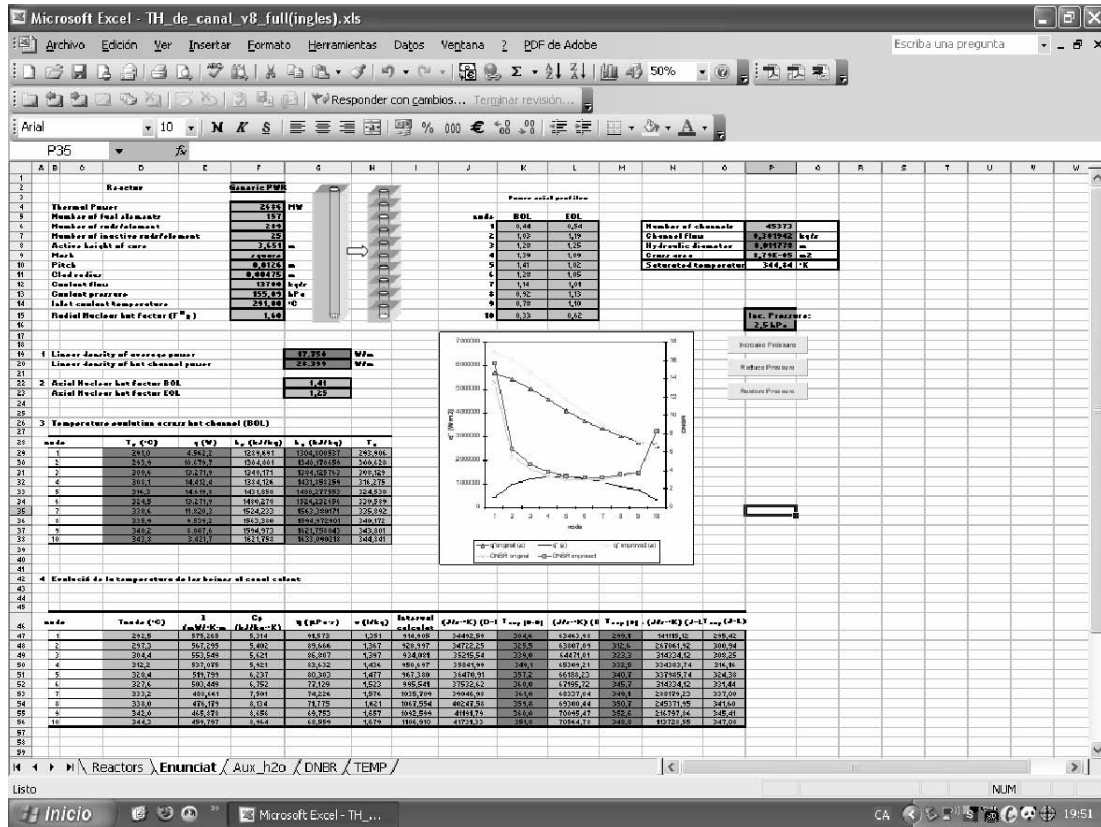


Fig. 1. Worksheet general view.

fied for a narrow range of application. Finally, any actual problem needs a large number of equations to be solved and their resolution requires sophisticated numerical methods and huge computing resources.

Fortunately, this problem has been solved by the international community of thermalhydraulic analysts. The main tools that currently help to provide this solution are codes and models (or nodalizations) [6]. Codes and nodalizations help analysts to solve sophisticated multi-dimensional equations, deal with complex correlations, and ensure the transition between them at the limit of their field of application. Using such tools, teaching how to do it and training users is a well-consolidated activity at UPC as well as at a large number of technical universities [7]. Nevertheless, being effective in the early stages of the learning activities leading to such knowledge needs some pedagogical care.

Our objective here is to present and discuss some pedagogical concepts devoted to produce efficient results in the very first steps of learning THNPP. For this purpose a specific educational worksheet (Fig. 1) has been developed at UPC and it is described with some comments on its most relevant features.

In both cases (degree or master) the starting point is defined in a very similar way:

- Students are having their first contact with THNPP
- Students having the intention to choose a THNPP thesis are mixed with the others
- Basic THNPP concepts are complex and just being introduced.

Besides, organizing student workload in order to enhance lecture effectiveness is an important issue to be considered.

Although the intention is to focus on pedagogical justification, this never comes alone. So, the development explained below has obviously some parts devoted to technical concepts and to the tool itself, and some others to the pedagogical aspects involved.

MAIN CONCERNS

General concepts must be clear. Ideas related to quantitative concepts involved in calculations can be presented at a theoretical level, but at an early stage it is important to strengthen them at a practical level. Students of nuclear engineering, like many others, need to perform calculations with an increasing level of difficulty in order to fulfil two basic goals: to confirm correct learning of concepts and to start using calculating tools in a practical way.

It is important to state that codes and nodalizations are tools that help analysts to perform calculations. Analysts or code users are the crucial agents of activities aimed at producing results. It is

widely accepted that, along with qualified codes and nodalizations [8], both the nuclear industry and research groups need qualified users of established tools [9, 10]. To provide qualified users, education and training are an essential step that has to be properly taken [7].

Within the current context of European higher education, universities need to ensure that calculation exercises involving an effective increasing level of difficulty are consistently prepared and supplied to students. Only if this preparation work is properly carried out will the change process become a reality and student workload will provide fruitful results.

Calculations need to be performed from the very beginning and they must be consistent with teaching at the university in a first stage, and with more specific training within industry and research later on. Using a properly organized worksheet, a limited number of teaching sessions with corresponding study on the part of the student provide interesting results to consolidate knowledge of the most relevant aspects of PWR core thermalhydraulics. Such an initiative needs to start limiting the scope of the exercise: in this case the strategy is to limit the analysis to a PWR core and to leave the study of other systems and components (such as pipes, pumps, steam generators or others) for the future. All this work has been carried out bearing in mind the fact that the worksheet is a first step in the practical use of calculation codes and mainly a help for the consolidation of calculation concepts.

From the beginning, some easy calculations are performed by students using a standard worksheet which will allow them to concentrate on concepts and parameters related to phenomena, and thus on the general understanding of a basic overview of the physics involved. All this learning is accompanied by some simple, but realistic, results produced by the student.

BALANCE EQUATIONS: ENERGY BALANCE

Balance equations belong to the fundamentals of codes. All codes solve balance equations of the three essential physical magnitudes; energy, mass, and momentum for dynamic scenarios. The solution has to be complete, including the treatment of non-homogeneous and non-equilibrium situations. This is the only way that thermalhydraulic codes can become a valuable tool to address safety scenarios in which neither homogeneity nor thermodynamic equilibrium are assumed a priori. In addition, if codes are specifically used for water reactors, as it is the case of RELAP5 [11], or TRACE [12], they need to deal with two-phase flow, two-phase balances, steam generation, inter-phase mechanical interaction, stratification, and other phenomena involving phase separation.

In order to prepare a block of practical exercises

that are useful for students having their first contact with reactor thermal-hydraulic analysis, it is clear that some simplifications have to be performed. It is also clear that both theoretical lectures and future practical exercises need to proceed with a full explanation of phenomena involved in safety scenarios and their related thermodynamics. The use of codes must be ensured in advanced practical exercises.

The proposed exercise focuses on energy balance and starts with homogeneous equilibrium situations. It is a tough simplification that is justified following a strictly educational rationale. Getting rid of such an important feature of the physical picture of the actual behavior of a liquid-gas mixture at this stage is only acceptable because other important calculation concepts have to be presented by the instructor and learned and consolidated by the student.

At a theoretical level, energy, mass, and momentum balance equations are developed and posed in their fully developed form for steam and liquid water. But the first practical balance exercise refers to a steady state scenario at constant mass flow. In this exercise, a certain amount of energy is absorbed by the fluid, which increases its temperature, and perhaps even reaches local boiling.

If viscous dissipations are neglected (power density due to dissipation is several orders of magnitude smaller than the nuclear power density [13]), and combining total and kinetic differential energy equations, a differential thermal energy equation can be written as follows [13]:

$$\rho \frac{Dh}{Dt} = -\nabla \bar{q}'' + q''' + \frac{Dp}{Dt} \quad [a]$$

Where:

- ρ = water density
- h = water enthalpy
- p = water pressure
- \bar{q}'' = surface heat flux
- q''' = volume heat source
- t = time

$$\frac{D\bullet}{Dt} = \frac{\partial \bullet}{\partial t} + \nabla(\vec{v}\bullet) \quad \text{is the material derivative}$$

\vec{v} = water velocity vector

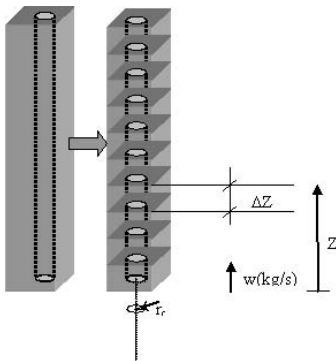


Fig. 3. Channel scheme.

For the exercise, steady state is considered ($\partial/\partial t = 0$). In order to simplify, it is assumed that no heat generation ($q''' = 0$) exists in the fluid (i.e. direct moderator heating is not considered). Finally, the pressure gradient (even along the vertical direction) is neglected.

To apply the equation to the coolant fluid surrounding a given fuel rod, it is necessary to define the control volume and its boundaries. With Fig. 2 in mind, it is possible to define a control volume Ω as:

$$\Omega = \Delta x \cdot \Delta y \cdot \Delta z - \pi r_c^2 \Delta z$$

Where r_c stands for the outer radius of the fuel cladding. The boundary contours of Ω , A , are defined as a sum of the lateral surface (A_l), the cross-sectional surface (A_f), and the fuel rod surface (A_r).

Continuing with the simplifications, one directional flow is considered (along the z coordinate, parallel to the rod axis). The surface heat flux (q'') term is positive in the fuel rod surface (A_r) and zero in the other surfaces (i.e. no heat transfer between adjacent control volumes), and it is assumed that q'' varies only along the z coordinate.

Integrating and using the assumptions above, Equation [a] becomes:

$$w \Delta h = \bar{q}' \Delta z \quad [b]$$

Where $w = \rho v A_f$ is the (constant) water mass flow and \bar{q}' the mean linear power density of the fuel rod:

$$\bar{q}' = \int_{\Delta z} q' dz = \int_{\Delta z} 2\pi r_c q'' dz$$

This development could be obtained also from the phasic energy equations applied in codes like RELAP5 with the only extra assumption that no phase change appears (Eq. 3.1–11 and 3.1–12 in [11]).

The omission of the pressure term in Equation [a] is equivalent to neglecting the gravitational and kinetic energy terms in the lumped parameter integral energy equation. This equation [13], assuming steady state, one direction flow and heat power from fuel rods as the only energy addition, can be written as:

$$w \left(\Delta h + \frac{1}{2} \Delta v^2 + g \Delta z \right) = \bar{q}' \Delta z$$

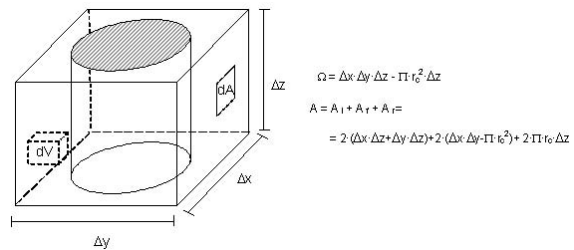


Fig. 2. Control volume scheme.

In the normal operation of a PWR core, the second and third terms on the left-hand side are negligible (they are several orders of magnitude smaller) in front of the enthalpy term.

For the application of equation [b] in the worksheet, a fixed number of 10 axial nodes over the whole core are used as can be seen in Fig. 3. The inlet temperature of each node is the outlet temperature of the previous one. The inlet temperature of the first node is the temperature at the core inlet, recalled from initial data. w , q' and Δz are results of preliminary calculations and only refer to original data, geometry and number of nodes. The assumption that a pressure gradient does not exist makes obtaining enthalpy from temperature, or temperature from enthalpy, an easy calculation. Δh in each node, therefore, becomes a direct calculation using equation [b].

The application is useful in order to explain the concept of node, and to discuss exactly what it is. In addition, it helps to introduce the concept of "centred value" and value at the border of the node.

WATER PROPERTIES: STEAM TABLES

Algorithms providing water properties, such as temperature, pressure, enthalpy, or other magnitudes are an important element of full codes. For each time step, and even for each iterative computation, a devoted subroutine of the code provides values of the necessary state variable and other water properties. This dedicated subroutine starts from two known state variables that are considered as the arguments, and provides the values of the selected parameters.

Although some software solutions already exist and are available, at the time that this worksheet was prepared it was decided to draw up our own single, integrated auxiliary worksheet to obtain water and steam properties. This auxiliary worksheet contains an initial matrix of water properties and uses the FORECAST excel feature to calculate

properties at any state that can be interpolated. Saturation temperatures at each pressure are also considered. Table 1 shows a partial view of the water properties auxiliary worksheet.

One of the advantages of this section of the worksheet is that the student will easily recognise that the information needed comes from a known reference (water properties and steam tables [14]) extensively used during university studies at different stages. Codes treat them in a complete form, but basically use the same idea.

HEAT TRANSFER CORRELATIONS: SELECTING HEAT TRANSFER PATTERN

Heat transfer correlations are, in a similar way to balance equations, part of the fundamentals of codes. All codes use a significant number of heat transfer correlations together with the laws that drive the calculation in order to select the correct approach. The chosen approach is also a function of coolant state, coolant hydrodynamics and heat transfer itself. The code usually makes a decision at each time step following coded principles. Selecting a heat transfer pattern is a complex issue and is automated in the code. A code such as RELAP5 [11] implements a large number of different modes of heat transfer from wall to fluid depending on the combination of phenomena such as presence of non-condensables, one or two phases, nucleate boiling (sub-cooled or saturated), transition or film boiling, condensation. The RELAP5 wall heat flow chart is a complicated diagram. Again, it is clear that some simplification is needed for any block of practical exercises to be carried out by beginners. It is also clear that theoretical lectures and future practical exercises with codes have to proceed with a full explanation of the phenomena involved.

In this case the proposed exercise focuses on two different heat transfer patterns: one-phase liquid forced convection, and nucleate sub-cooled boiling. Each pattern can be seen in the RELAP5 flow

Table 1. Water and steam properties. Auxiliary worksheet (partial view).

P (bar)	T (°C)	V (l/kg)	h (kJ/kg)	Cp (kJ/ kg · K)	λ (mW/(K · m))	η (Pa · s)	h_L (kJ/kg)	h_V (kJ/kg)
...
130	325.0	1.5193	1489.0	6.703	502.4	77.09	—	—
140	325.0	1.5111	1487.0	6.577	505.6	77.65	—	—
150	325.0	1.5033	1484.0	6.465	508.6	78.18	—	—
160	325.0	1.4960	1482.0	6.364	511.6	78.69	—	—
130	330.8	1.5662	1530.0	7.274	487.4	74.22	1532.0	2667.0
140	336.7	1.6096	1570.0	7.836	475.4	71.85	1571.6	2642.4
150	342.1	1.6571	1609.0	8.551	464.0	69.50	1611.0	2615.0
160	347.3	1.7099	1649.0	9.498	453.1	67.13	1650.5	2584.9
157.6	250.0	1.2315	1085.0	4.716	635.8	109.35	—	—
	275.0	1.2929	1206.2	4.989	604.5	98.56	—	—
	300.0	1.3749	1336.2	5.443	563.2	88.67	—	—
	325.0	1.4978	1482.4	6.388	510.8	78.56	—	—
	346.2	1.6959	1639.3	9.216	455.5	67.70	1640.9	2592.8

chart and has its own correlation along with ranges of application. The correlation selection logic can be derived from the ranges and is thus implemented.

For forced convection the correlation used is that of Dittus-Boelter in both RELAP5 and the worksheet, and can be written as follows:

$$\text{Nu} = 0.023\text{Pr}^{0.4}\text{Re}^{0.8} = \frac{h_s D_h}{k} \quad [c]$$

where:

- Nu = Nusselt number
- Pr = Prandtl number
- Re = Reynolds number
- h_s = Heat transfer coefficient (W/(m² K))
- D_h = Hydraulic diameter (m)
- k = Coolant thermal conductivity (W/(mK))

The Dittus-Boelter correlation can be used provided the temperature in the cladding surface is below water saturation temperature ($T_{clad} < T_{sat}$).

For nucleate sub-cooled boiling the correlation used in the worksheet is that of Bernath [d] and can be written, in British Units, as follows [15]:

$$h_s = 10890 \frac{D_h}{D_i + D_h} + 48 \frac{v}{D_h^{0.6}} \quad [d]$$

where:

- h_s = Heat transfer coefficient (Btu/(h ft² °F))
- D_i = Heated Diameter = (Heated perimeter)/ π (ft)
- D_h = Hydraulic diameter (ft)
- v = Coolant velocity (ft/s)

The range of validity of Bernath correlation is established as $T_{sat} < T_{clad} < T_{sc}$, where T_{sc} is also a function of coolant conditions and will not be discussed in this paper [15].

Although it is known that other correlations give better results [11, 13], Bernath correlation is chosen due to its simplicity. It does not need any iterative calculation as the heat transfer coefficient comes directly from geometry, state variables, and coolant velocity.

Observing ranges of validity of both correlations, adequate programming could help to introduce an important calculation concept: the selection of the right correlation as a result of the thermal-hydraulic calculated state. This idea will be learned and consolidated by the students themselves.

The application in the worksheet uses Newton's law [e]

$$q'' = h_s(T_{clad} - T_{fluid}) \quad [e]$$

or

$$T_{clad} = T_{fluid} + q''/h_s$$

and starts calculating two different cladding temperatures (T_{clad}) using the two different heat transfer coefficients (h_s): $T_{clad-DB}$ (using Dittus-Boelter correlation) and T_{clad-B} (using Bernath

correlation). Because the nature of both correlations, always $T_{clad-DB} > T_{clad-B}$, Then, the logic followed is:

- If $T_{clad-DB} < T_{sat}$ then $T_{clad} = T_{clad-DB}$
- If $T_{clad-B} > T_{sat}$ then $T_{clad} = T_{clad-B}$

Finally, if $T_{clad-DB} > T_{sat}$ but $T_{clad-B} < T_{sat}$ the calculation is in a transition node and a smooth evolution has to be applied. For simplicity, the transition proposed in the basic worksheet is to set such nodes to $T_{clad} = T_{sat}$. The solution is very straightforward and is not far from what could be reasonably expected for a steady state situation. In this case the lecturer could inform the student that when studying scenarios close to boiling crisis, things will not be smooth at all and a sharp increase can be expected for T_{clad} axial profile.

Back to correlations [c] and [d], an important quantity of water properties have to be looked up in the table. Each value of conductivity, viscosity, density, or specific heat needed by each of the two correlations has to be adequate for the state conditions of the coolant in the node. Again, the student can ask him or herself: "Is the correlation to be calculated in the centre of the node or is it on the border of the node?" The answer, in this case, depends on whether the calculation intends to be a BE (best estimate) or a conservative calculation. At this stage the lecturer has an opportunity to start introducing these two concepts.

If the calculation goes ahead assuming that the temperature of the node is the highest temperature the node could have, the calculation will have an inherent conservatism. The results will be helpful in ensuring that thermal design limits will be kept, but the predicted phenomenology will not be realistic.

The application is also useful to show a simple solution that produces quite a smooth transition between heat transfer patterns. Obviously, more sophisticated transitions can be coded, such as, for instance, to establish a weighted mean value of heat transfer coefficients calculated with both correlations for the transition node or nodes. This last solution is often implemented in standard codes.

As can be seen once again, concepts are introduced in a simple way but with an important immediacy to their use.

FUEL ROD THERMAL BEHAVIOR

Fuel rod thermal behavior, along with balance equations and correlations, also involves interesting concepts which require some explanation and practice. In this case, heat generation and conduction within the fuel rod and through the gap and the cladding, will be treated following equations that are available in the technical literature. Starting from a basic differential heat balance equation [16] such as:

$$q'''(r, t) - \nabla(-k\nabla(T(r, t))) = \partial/\partial t(\rho c T) \quad [f]$$

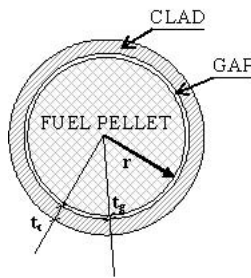


Fig. 4. Cell cross view.

two different integral equations for the radial temperature increase in the fuel rod, ΔT , can be derived, depending on whether there is heat generation in the region [g] (fuel pellet) or not [h] (gap and cladding).

$$\Delta T = (q'''r^2)/(4k) \quad [g]$$

$$\Delta T = (q't_g)/(2\pi rk) \quad [h]$$

The basic application in the worksheet assumes one zone for the pellet, one for the gap, and one for the cladding, as can be seen in Fig. 4. The thermal conductivity of each material or gas space is provided as a function of average temperature.

The application uses the mathematical results from a text book recommended by the educational team [16], and thus ensures consistency of teaching organization and the methodology used.

USE OF THE WORKSHEET

Energy balance, steam tables, heat transfer correlations, and fuel rod behavior are pre-programmed in the instructor version of the worksheet following the scheme outlined above. The pre-programming includes not only equations and correlations but also decisions like selecting the heat transfer pattern. The instructor version of the worksheet is never supplied to the students. In doing so, despite getting quick results, the learning value would be minimal. The opposite situation, which is to let the student prepare all the development, could be good at the end, but it is not optimal for students having their first contact with the subject.

The worksheet has been used for the last three years with students having their first contact with NPP thermal-hydraulic analysis at the Technical University of Catalonia. After some introductory lectures (lasting no more than four or six hours) on general aspects of the broader subject in which THNPP is integrated (usually Nuclear Safety or Accident Analysis), a first practical session using the worksheet has usually resulted in an increase in student learning. At the beginning, students make a basic use of the worksheet.

The basic exercise starts with some general data on a reactor. Table 2 shows an example of a set of

Table 2. Reactor general data

Reactor	Generic PWR	
Thermal Power	2686	MW
Number of fuel elements	157	
Number of rods per element	289	
Number of inactive rods per element	25	
Active height of core	3.651	m
Mesh	square	
Pitch	0.0126	m
External cladding radius	0.00475	m
Coolant flow rate	13700	kg/s
Coolant pressure	15.51	MPa
Inlet coolant temperature	291	°C
Radial Nuclear Hot Factor (F_{NR}^N)	1.6	

Table 3. Reactor power axial profiles

node	Begin Of Life	End Of Life
1	0.44	0.54
2	1.03	1.19
3	1.28	1.25
4	1.39	1.09
5	1.41	1.02
6	1.28	1.05
7	1.14	1.01
8	0.92	1.13
9	0.78	1.10
10	0.33	0.62

Table 4. General results

	Units	
Number of channels	45373	
Channel flow	0.302	kg/s
Hydraulic diameter	0.0118	m
Flow area	8.79E-05	m ²
Saturation Temperature	344.84	°C

such data, and Table 3 provides the power axial profiles that have to be used. It is clear that these input values can be changed and adapted to other PWRs. From these data, the student must calculate some preliminary results which are the general features of the problem, such as mass flow per fuel rod or power per node. The chosen reactor geometry must be discussed and students need to come up with the right picture of core thermal behavior at a nominal steady state. This preliminary part also helps to clarify radial and axial power peaking factors, as well as the different ways power is usually normalized. Table 4 shows some of the above-mentioned general results.

After some practice in use of the worksheet, some procedures and guidelines were established. Most of the times, the structure of the worksheet is given to the students with some formulae erased. The student has to start working on the computer but not alone: he or she is helped by the structure of the worksheet to rebuild the parts that have been deleted.

The student need not build everything. Existing equations work as a kind of example of how the others can be programmed and so are helpful to build (or rebuild) those that have been deleted. The

Table 5. Energy balance results

node	T inlet (°C)	q (W)	h inlet (kJ/kg)	h outlet (kJ/kg)	T outlet (°C)
1	291.0	4562	1289.7	1304.8	293.9
2	293.9	10680	1304.8	1340.2	300.6
3	300.6	13272	1340.2	1384.1	308.1
4	308.1	14412	1384.1	1431.9	316.2
5	316.2	14620	1431.9	1480.3	324.5
6	324.5	13272	1480.3	1524.2	330.5
7	330.5	11820	1524.2	1563.4	335.8
8	335.8	9539	1563.4	1595.0	340.1
9	340.1	8088	1595.0	1621.8	343.8
10	343.8	3422	1621.8	1633.1	344.8

structure of the worksheet is common to the entire group of students and this facilitates the task of the instructor.

Typically, the first formula erased by the lecturer is that related to energy balance in the first node. The student then has to think about applying equation [b] starting with a known value of the inlet temperature and the constant mass flow calculated in the preliminary part of the exercise. Equation [b] is written in terms of enthalpy, so the necessary enthalpy has to be produced by the water properties sheet. The constructed formula is then copied to the other nodes. Table 5 shows the results of this part of the exercise. Although it is a simple task within a worksheet, a question may arise. The obtained result seems to be enthalpy or temperature at the border of the node. Is this temperature the right one to consult water properties or is it more convenient to calculate the average temperature of the node? The question asked by the student can also be answered by the student. The method helps the student discover, as part of a simple calculation, concepts that will appear later on in a more difficult context.

Educators are recommended not to do everything on the first day. The procedure of erasing formulae is powerful, although some caution is suggested. If too many things are deleted, the educational guideline is not helpful.

If two different heat transfer patterns are specified, and their corresponding heat transfer correlations are given, it is educationally interesting not to erase both of them. The suggestion is to let the

student read and understand the programming solution of one of them and to erase the other or even only part of the other equation. In this case, after some practice, the best thing is to let the student concentrate on programming the selection of the right correlation out of the two proposed patterns, as in the application of smoothing the transition between patterns.

Most students manage to calculate the cladding temperature as a function of the position in the reactor, as in Fig. 5.

Basic use of the worksheet is completed with some work on fuel rod behavior. Normally, students are asked to perform some sensitivity calculations in order to understand the importance of material properties in the final results.

From values obtained, such as cladding temperature (see Fig. 5) for the hot channel, equations [g] and [h] are used to obtain fuel maximum temperature for different values of gap thermal resistance and fuel conductivity. This basic application is not the only way this issue is treated in the worksheet. More options are suggested below.

After two hours using the worksheet while assisted by the educator, the students take it home and, in many cases, learning improvement is really impressive.

STUDENT ASSIGNMENTS

After three years experience of supplying the worksheet to students, its use is normally understood at the end of the assisted session of two hours. Once students take the worksheet home, they are asked to use it as they wish. It is important to note that in parallel with home use, the students attend new lectures where new concepts are being developed. Normally, the concerns of students can be classified into two different categories:

- Those dealing with completing the first basic exercise.
- Those related to what is going on in new lectures.

The work usually developed for the former category is normally mandatory and students

Node	Tclad (°C)
1	304,6
2	325,5
3	339,0
4	344,8
5	344,8
6	345,7
7	349,1
8	350,7
9	352,6
10	348,8

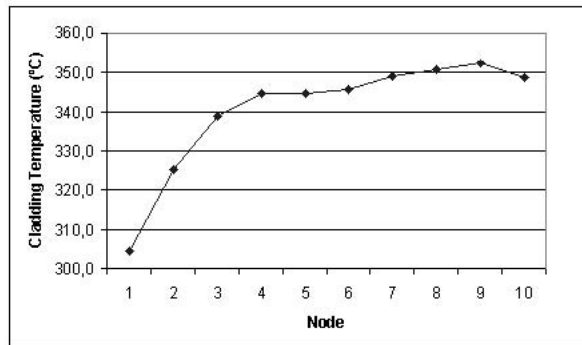


Fig. 5. Cladding temperature as a function of the position in the reactor.

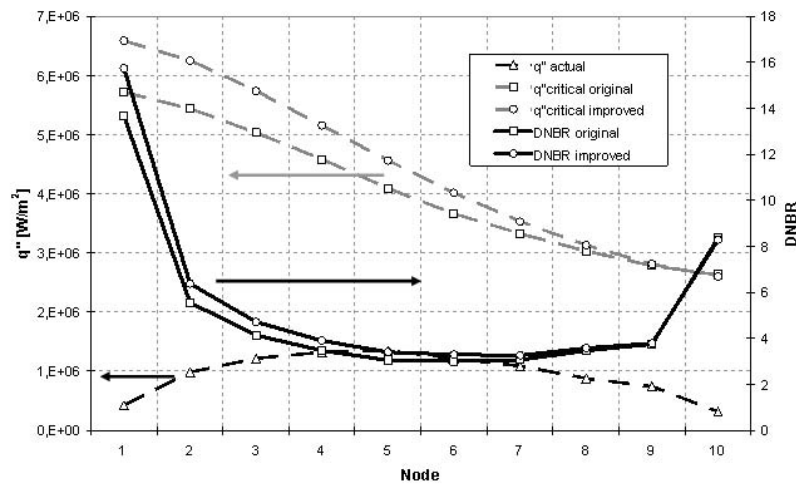


Fig. 6. Departure from Nuclear Boiling Ratio (DNBR) and q'' as function of axial position in core.

complete it in a limited time. On the whole, results are interesting because important feedback is obtained from the different students' calculations:

- Different kinds of reactors are considered.
- Sensitivity calculations on fuel properties are evaluated.
- The impact of high values of radial peaking factor is studied.
- Low coolant flow scenarios are considered.
- Low pressure scenarios are considered.

Results from the latter category are also interesting, but in a different way. Delivering results is not mandatory and consequently time is not limited. The obtained feedback is not abundant, but its excellence is visible. Again a list helps to emphasise this:

- Simple DNBR (Departure from Nucleate Boiling Ratio, i.e. the ratio between critical and actual heat fluxes [16]) correlation is coded.
- Heat transfer correlations are compared.
- DNBR correlations are compared.
- Multiple zone in pellet nodding is established.
- A pseudo-dynamic use of the worksheet is established.

All student feedback has been analyzed over a three-year period and used to improve some features of the basic structure of the worksheet. The most usual questions that arise have already been answered and have been added as comments on the worksheet itself. Misunderstandings that are revealed as being more frequent are avoided or clarified from the very beginning.

In addition, some parts of the content of theoretical lectures have also been developed or simplified taking into account the fact that some concepts have already been learnt by the students during their assignments. Safety scenarios involving either low primary pressure or low core flow are a clear example of this: once these subjects appear in theoretical lectures the educator realizes

that students already have their own understanding of the most relevant phenomena involved.

Among student feedback following more advanced use of the worksheet, two observations are especially interesting:

- Comparing heat transfer and DNBR correlations
- Establishing a pseudo-dynamic use of the worksheet.

The main reason for using Bernath correlations for both heat transfer and DNBR was their simplicity. As the exercise was intended for students having their first contact with core thermalhydraulic analysis, it was necessary to start with straightforward correlations. The objective of the assignments of the first selected group of students was to evaluate the accuracy of Bernath correlations. A significant number of students decided to apply other correlations for both heat transfer and DNBR. Some complicated correlations such as those of Chen for heat transfer [13] and Tong for DNBR [17] were implemented and the results were compared. The results of these comparisons are useful today in the introductory session, when the educator justifies the simplifications performed in the basic worksheet. As an example, Fig. 6 shows DNBR and q'' as a function of the position in the reactor using two different DNBR correlations: Bernath correlation (the original approach) and Tong correlation (a more refined approach).

The second item of feedback was related to the pseudo-dynamic use of the worksheet. The Excel worksheet becomes even more flexible and powerful if its visual basic programming capabilities are taken into account. In other words, a pseudo-dynamic exercise can be performed by preparing a single script associated with a control button. From the programming point of view there is no complexity: coolant pressure increases when the control button is clicked and the script recalculates all the cells and graphical outputs on the work-

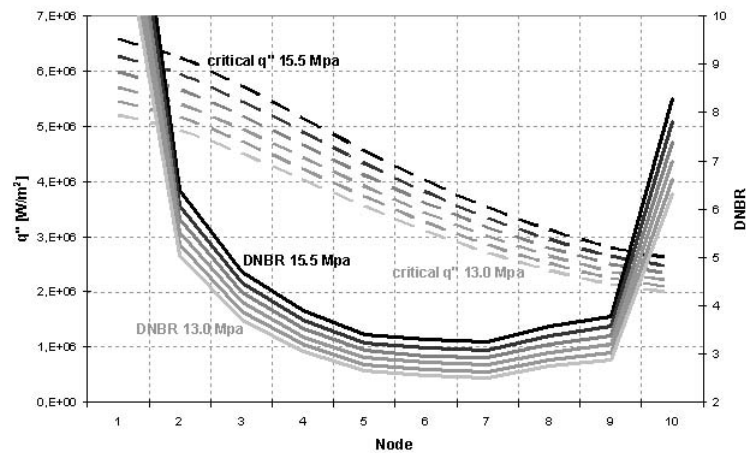


Fig. 7. Evolution of critical heat flux and DNBR after different pressure drop steps.

sheet. The value of such a positive or negative increase of pressure is established by the student in a dedicated cell.

Because of the low calculation load in the worksheet, the new output values and graphics appear immediately and reiterated activation of the control button leads to a kind of pseudo-dynamic simulation where temperatures, heat fluxes and DNBRs evolve simultaneously with the pressure. Figure 7 shows the simulated evolution of critical heat flux and the related DNBR values when the pressure of the coolant in the simulated reactor drops from 15.5 MPa to 13.0 MPa following subsequent small pressure steps. The final results are not far from what can be expected during slow depressurization of the primary circuit in which the quasi-static approach is applicable.

Similar pseudo-dynamic exercises can be performed by considering discrete variations of other boundary conditions such as inlet coolant temperature or coolant flow rate, among others.

CONCLUSIONS

We have described a useful tool for teaching basic thermalhydraulics of a PWR core using a

standard worksheet. Guidelines for practical exercises are included and justified. The worksheet is significantly helpful for fulfilling the objectives of European higher education as it efficiently encourages improvement in learning based on student workload. It provides interesting results and helps to consolidate knowledge of the most relevant aspects of thermal-hydraulics of a PWR core. It is also an open tool that can be improved following student development, as is shown above.

The worksheet is compatible with the use of codes and models that will appear later in the course with a high effectiveness since concepts and parameters related to physical phenomena are successfully clarified at an early stage following exercises of increasing difficulty.

The worksheet has been tested and is being currently used at UPC (Technical University of Catalonia) with interesting educational results.

With this development, we have also shown a general philosophy of how the educator involved in teaching technology subjects can take advantage of a student assignment in order to enhance theoretical lectures and assisted practical sessions. This philosophy can also be applied to other fields of engineering education.

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