THERMAL ASSESSMENT OF THE CALIPSO IRRADIATION DEVICE FOR THE JULES HOROWITZ REACTOR

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ABSTRACT

A good knowledge of the temperature of samples in Material Test Reactors (MTR) is of the utmost importance for material irradiation. Best results have been obtained up to now using a stagnant liquid metal like NaK as the fluid environment ; however the search for better temperature control requires having the liquid metal flowing around the samples. This is the aim of the CALIPSO device, a NaK loop for material irradiation in the core of the Jules Horowitz Reactor (JHR).

Progress on the detailed design of this innovative device has been made concerning its geometry and its main components such as the electromagnetic pump, the electrical heater and the heat exchanger. Its overall dimensions have been defined according to the safety requirements and regulatory rules.

Along with technological development, extended thermal calculations have been performed since the beginning of the project. The present paper describes the results obtained with an optimized geometry.

To quantify the experimental performance of such an irradiation device, a stringent quality criterion of 7.5℃ on the NaK temperature difference over a 55cm-long sample zone has been defined. The study covered a large nuclear heating range (5 W/g – 21 W/g) and NaK temperature from 150℃ to 450℃.

The analysis of results leads to the main following observations:

- sample shape and type of material have a large influence on the NaK temperature level,
- to provide a large optimal operating range regarding nuclear heating values and NaK temperature, it is necessary to have different lengths of heat exchanger,
- NaK flowrate has to be kept constant during normal operating conditions : 1.5 m^3/h to 2 m^3/h is the optimal range,
- during irradiation, the best way to compensate temperature changes is to adjust the electrical power of the heaters.

This study highlights the flexibility of CALIPSO to reach required thermal conditions for samples under irradiation in different locations of the reactor core.

1. INTRODUCTION

A good knowledge of the temperature of samples in Material Test Reactors (MTR) is of the utmost importance for material irradiation, in particular when it comes to study zones where properties can change drastically with respect to temperature. Best results have been obtained up to now using a stagnant liquid metal such as NaK as the fluid environment. Its effect is to better homogenize and control the temperature at the surface of the samples particularly when using non axisymmetrical loading in very high gamma ray flux. The search for a better temperature control and the reduction of experimental uncertainties, driven in particular by thorough mechanical and chemical property studies, requires having a liquid metal flowing around the samples.

Under the framework of the Jules Horowitz Reactor (JHR) project, a NaK metal liquid loop for in-core material irradiation experiments is under development (1) (2). Initially known as "M3" in its conceptual design (3), this test device has been named CALIPSO since the beginning of its detailed design. As summarized in its acronym it is an in-Core Advanced Loop for Irradiation in Potassium Sodium (NaK) coolant.

Progress on the detailed design of the CALIPSO device has been made concerning its overall geometry and its main components such as the electromagnetic pump, the electrical heater and the heat exchanger (4). The overall dimensions of the tubes have been defined according to the safety requirements and regulatory rules.
Along with technological development, extended thermal calculations have been performed since the beginning of the project. The present paper describes the results obtained with the geometry of the detailed design. Analysis was carried out to quantify the experimental performance of such an irradiation device, taking into account several values of nuclear heating and covering a large range of NaK temperatures.
After a short presentation of the loop and its main components, this paper will detail the thermal modeling and the main calculation results. Finally, the analysis of the main parameters of influence will lead to suggestions for the operating strategy of CALIPSO.

2. GENERAL DESCRIPTION

The overall length of CALIPSO is 6800 mm and its outer diameter is 33 mm in the lower part so that it can fit into the central hole of JHR fuel elements. Just above the fissile zone and up to the interface with the core vessel, the diameter is 83 mm. Finally, the upper part is 138 mm large for electrical connections, gas control and rig handling (Figure 1).
The containment rig is a double wall shell that fits to the core mechanical structures. It is cooled by the water of the reactor primary circuit.
A sample-holder is plugged into the containment rig through the circular opening situated in the upper part. It holds the material samples and experimental instrumentation. The present study is based on a sample–holder with 15 tubular samples inside the 60 cm long of the fissile zone (Figure 2). However, different sample holders could be designed to reach specific experimental objectives.

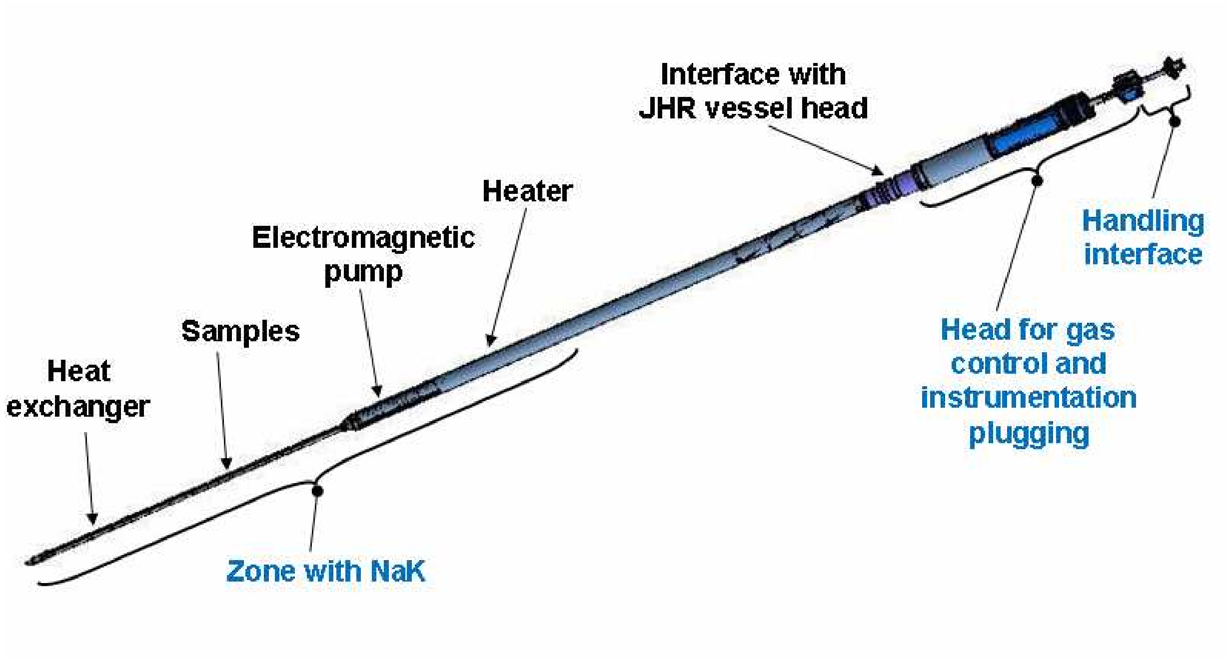

Figure 1 : General view of CALIPSO

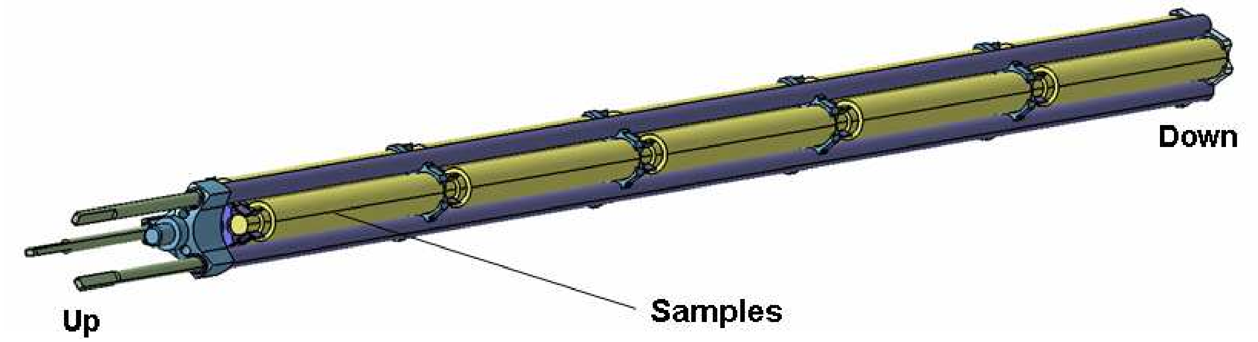

Figure 2 : Example with 15 samples : 5 levels of 3 samples placed at 120°

A 500 mm-long annular electromagnetic pump is located above the active zone in the containment rig. It is designed to fit in the available space of 78 mm in diameter and for the following operating conditions: NaK flow rate 2 m^3/h, pressure drop 1.25 bar and maximum NaK temperature 450°C (4). The NaK in the pumping channel flows from the bottom to the top.
An electrical heater is situated in the NaK just above the pump. Its maximum power is 18 kW over a total length of 400 mm. It allows the NaK to be heated before and after the flow reversal in order to adjust the operating conditions in the sample zone.
Energy transfer to the NaK flow due to nuclear heating occurs mainly in the active zone around the samples.
A heat-exchanger located at the lower part of the sample-holder, below the active zone, allows the NaK to cool down by heat transfer with the reactor primary circuit. (Figure 3)

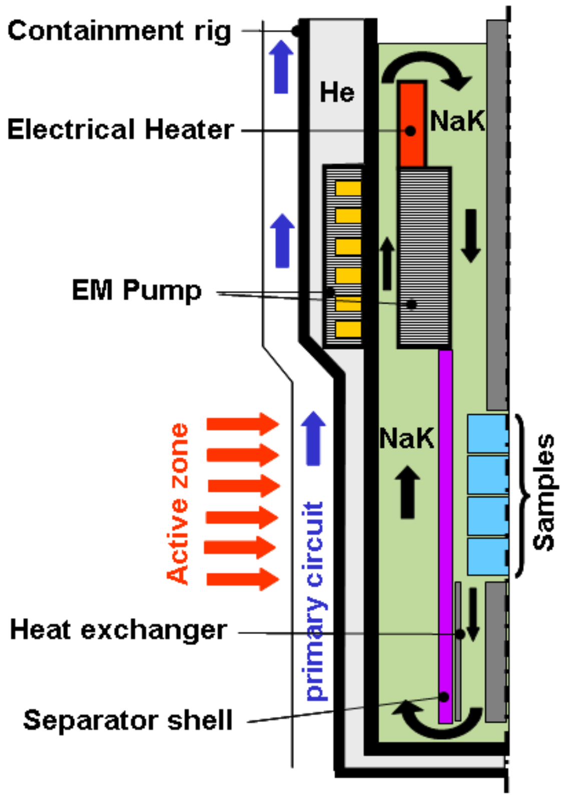

Figure 3 : Operating principle of CALIPSO

3. THERMAL MODELING

3.1 The REFLET code

The REFLET code was designed to perform steady state thermal calculations in axisymmetrical geometry, taking into account most of the specificities of irradiation test devices. With this software, radial heat exchanges and energy transport in fluid flows are considered, using analytical formulae. It is very convenient for large exploration of operating range and has been extensively used in the OSIRIS reactor for thermal prediction of experimental rigs and loops, both for material and fuel irradiations. In most of the cases the calculation results have been in good agreement with experimental measurements, confirming the pertinence of using REFLET in the design phase of new test devices for the Jules Horowitz Reactor.

3.2 Geometry

CALIPSO has been divided in 8 zones of different geometrical characteristics (Figure 4) : the main components (heat exchanger, samples, EM pump, electrical heater) and transition zones.
Each zone is characterized by its length and its radial geometry (external diameters of tubes). It is divided in slices to perform axial discretization. In each slice, temperatures and heat fluxes are calculated at the interface between materials : thermal balance are also performed in flowing coolants.
Because it is a component with a non-axisymmetrical geometry, the pump had to be simplified with an equivalent density and conductivity material.
Besides, exact geometry and material of the samples are not yet known. Thus, the hypothesis taken for their modeling is based on a 60 cm-long stainless steel tube situated in the active zone, its outer diameter being 18.6 mm and its thickness 2.05 mm. This geometry has been considered to simulate the actual sample holder presented Figure 2. Hydraulic section and material density were kept, but detail structures and instrumentation were neglected.

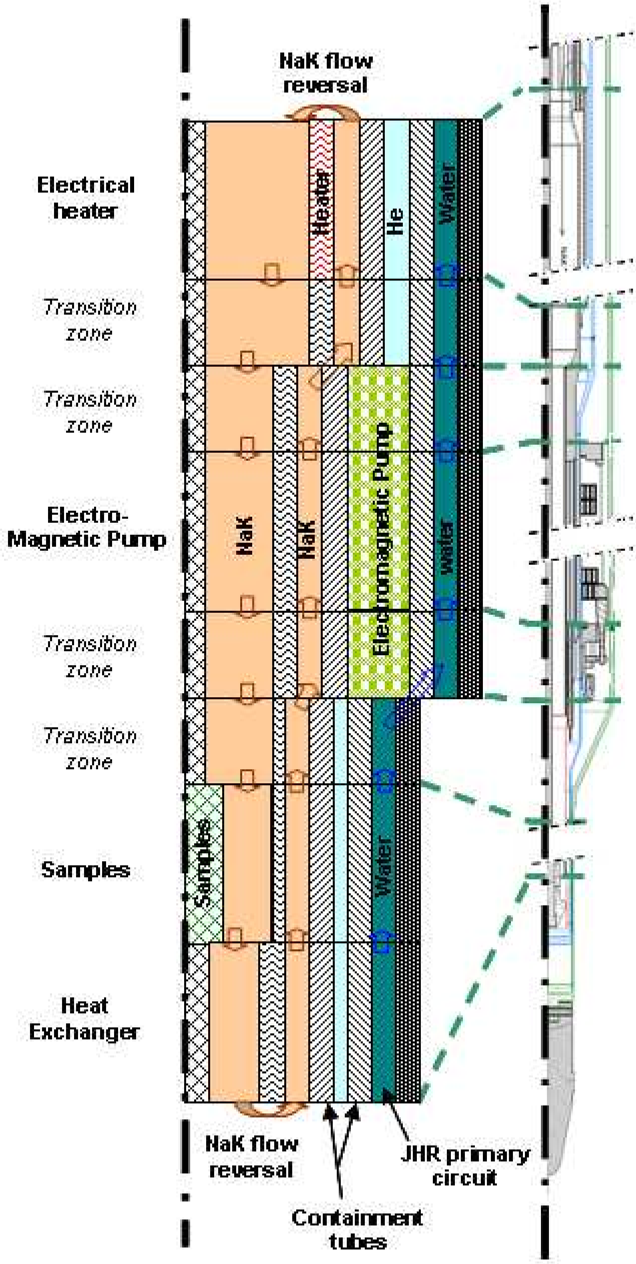

Figure 4 : Geometrical modeling

3.3 Nuclear heating

The nuclear heating profile is based on photonic calculations in the JHR core. It is similar in nature to a cosine shape in the active zone and exponential shape above and below the active zone.
A wide range of values for nuclear heating applied at the middle plane was explored in order to take into account different reactor power values, different locations of irradiation and calculation uncertainties. The studies were performed between 5 W/g to 21 W/g (referring to gamma heating in graphite). Weighting factors are used to take into account the response of different materials to gamma flux : for instance, nuclear heating is increased by 10% in steel.

3.4 Heat exchange with the primary circuit

The test device is cooled by the upward water flow of the JHR primary circuit. The inlet temperature is about 30℃ and the water speed in th e cooling channel surrounding the test device in the fissile zone is about 8 m/s. Thus, the heat transfer coefficient is very high, close to 3.5 10^4 $W.m^{-2}℃^{-1}$. In such conditions, the experimental device is not very sensitive to the variations of the primary circuit conditions in its normal operating range.

4. RESULTS

4.1 Quality criterion

To evaluate the thermal performance of the test device, a quality criterion has been given on the difference between the minimum and the maximum values of the NaK temperature in the test channel over the 550 mm of the sample zone. The limit of 7.5°C has been chosen to be considered as an optimum operating zone regarding experimental targets (Table 1).

Figure 5 presents an example of temperature profiles in NaK at an optimum operating adjustment. The upper curve (orange) is the NaK temperature in the central channel with downward flow. The interesting part is highlighted (red box) to show the criterion zone. The lower curve (green) is NaK temperature in the external channel with upward flow.

	Lower limit	Optimum	Upper limit
ΔT_{NaK} criterion	**7.5°C**	**2.2°C**	**7.5°C**
NaK mean temperature (over - 275mm and + 275 mm)	300°C	328°C	350°C
Power of electrical heater	5 925 W	10 075W	13 630W

Table 1 : Temperature criterion

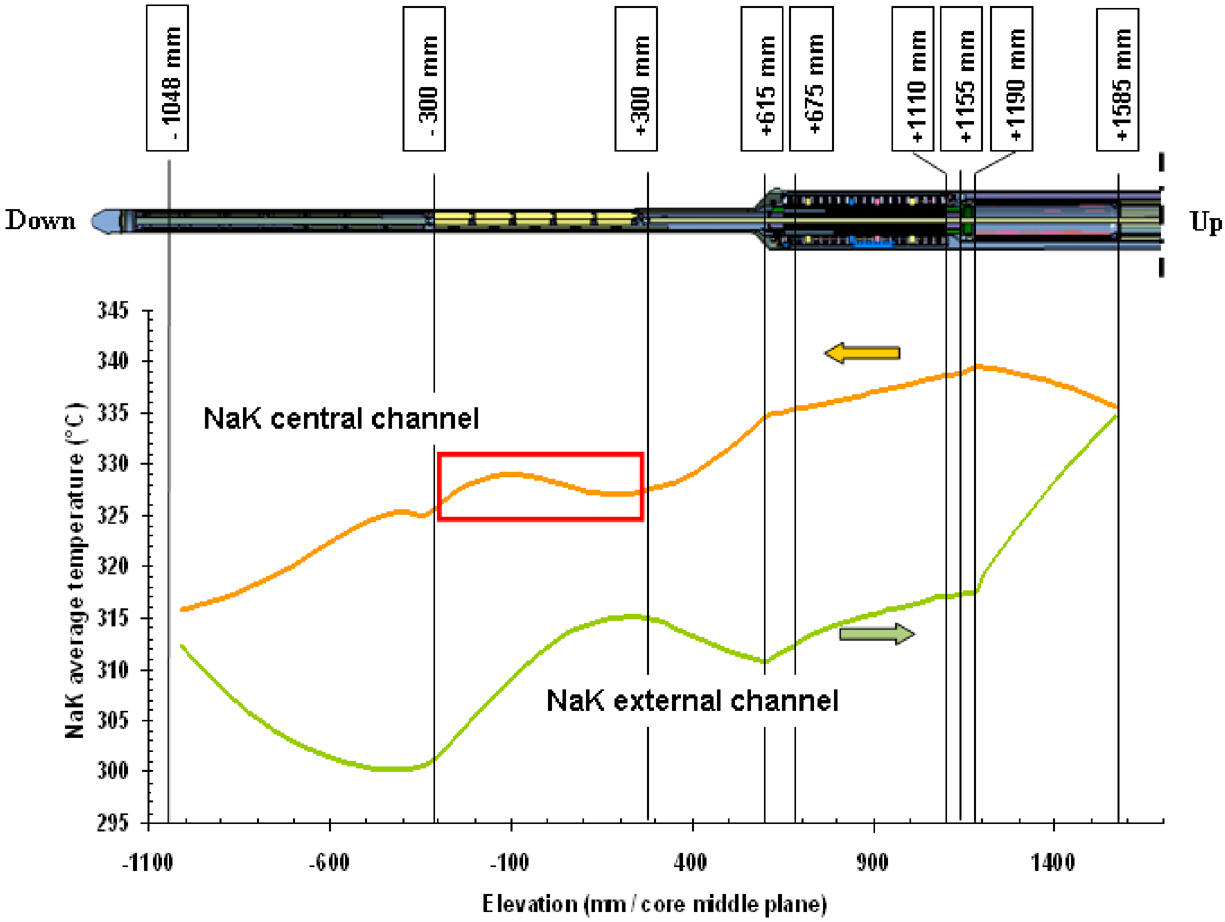

Figure 5 : NaK temperature profile for an optimum operating adjustment (nuclear heating 17.6 W/g, NaK flowrate 2 m^3/h, heat exchanger length 748 mm, electrical heating 10 kW)

4.2 Heat exchanger

Because nuclear power is a major contributor to the experimental heating conditions, the shape and the type of materials constituting the samples and the structure of the sample-holder itself have a large influence on the NaK temperature level. For instance, for a given nuclear heating, decreasing NaK speed around the sample shifts operating range to higher temperature while keeping good quality criterion. It is also the case for the same sample shape, but with higher material density in which nuclear heating is higher.

In order to adapt the NaK temperature level to the experimental needs for a given sample configuration, one possibility is to control heat loss to the primary circuit. This can be done by adjusting the length of exchange in the bottom of the rig, that is to say the level of NaK flow reversal (4). This point has been widely investigated.

The smaller the length of the heat exchanger, the higher the temperature will be. Figure 6 shows curves that can help to define which length of exchange is necessary to get the target NaK temperature for a given nuclear heating and a given sample arrangement. For instance, to get 350℃ in an in-core location with 10 W/g, a 100mm-long heat exchanger would be necessary, while a 748mm-long would be used for 20 W/g. If lower and higher limits of quality criterion are considered, the operating range is obviously enlarged for a given heat exchanger length.

Physical limits can be observed : nuclear heating in the core (orange vertical curves), safety limit based on 450℃ temperature of the containment rig (dashed black curve), electrical heater at zero power (dashed blue curve).

Modulation of the heat exchanger length will give flexibility to CALIPSO to cope with the quality criterion while covering a wide range of nuclear heating and NaK temperature for different types of samples. Adaptation of the heat exchanger length will be done in hot cells before the loading of the sample and will be kept at the same value during a reactor cycle.

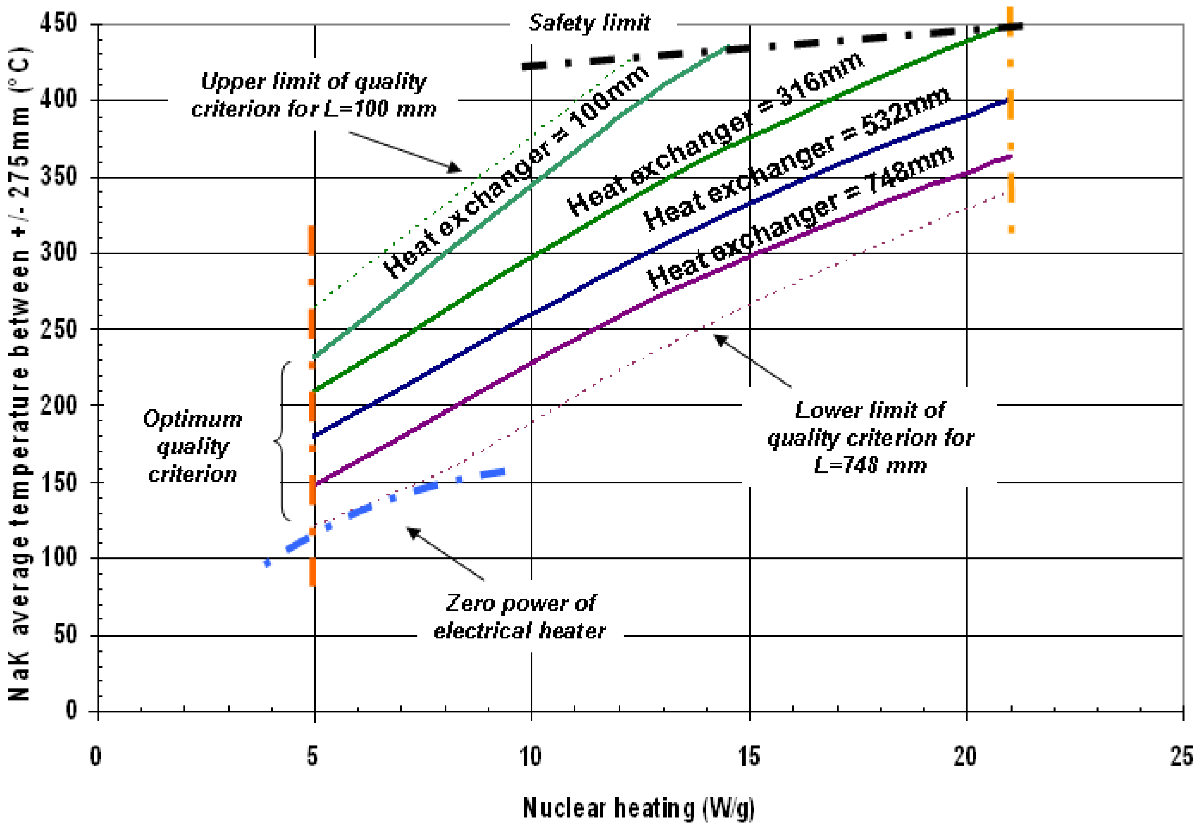

Figure 6 : Effect of heat exchanger length on NaK temperature

4.3 NaK Flowrate

The variations of NaK flowrate were also widely studied. Table 2 shows that the optimum value of the ΔT_{NaK} criterion increases with decreasing flowrate value ; it deviates outside of the limits (> 7.5℃) for a value of 1 m^3/h. However, the NaK mean temperature along the samples could be kept to the target value by adjusting the electrical heater power value.

Figure 7 shows an example of operating range based on curves obtained with the upper and lower limit of the heat exchanger length (see §4.2) and taking into account a quality criterion

of 7.5℃ with NaK flowrate value of 2 m^3/h (in red) and 1.5 m^3/h (in blue). It is obvious that the operating range decreases with flowrate value.
Below 1.25 m^3/h, the thermal performances are too poor with respect to the defined quality criterion. Higher flowrates than 2 m^3/h have not been considered due to electromagnetic pump limitation.

NaK flowrate	2 m^3/h	1.5 m^3/h	1.25 m^3/h	1 m^3/h
Optimum value of ΔT_{NaK} criterion	**2.2℃**	**3.7℃**	**5.2℃**	**8.4℃**
NaK mean temperature in the sample zone (over +/- 275mm)	328℃	320℃	319℃	321℃
Power of electrical heater	10 073 W	7 900 W	6 992 W	6 399 W

Table 2 : Effect of NaK flowrate (nuclear heating 17.6 W/g)

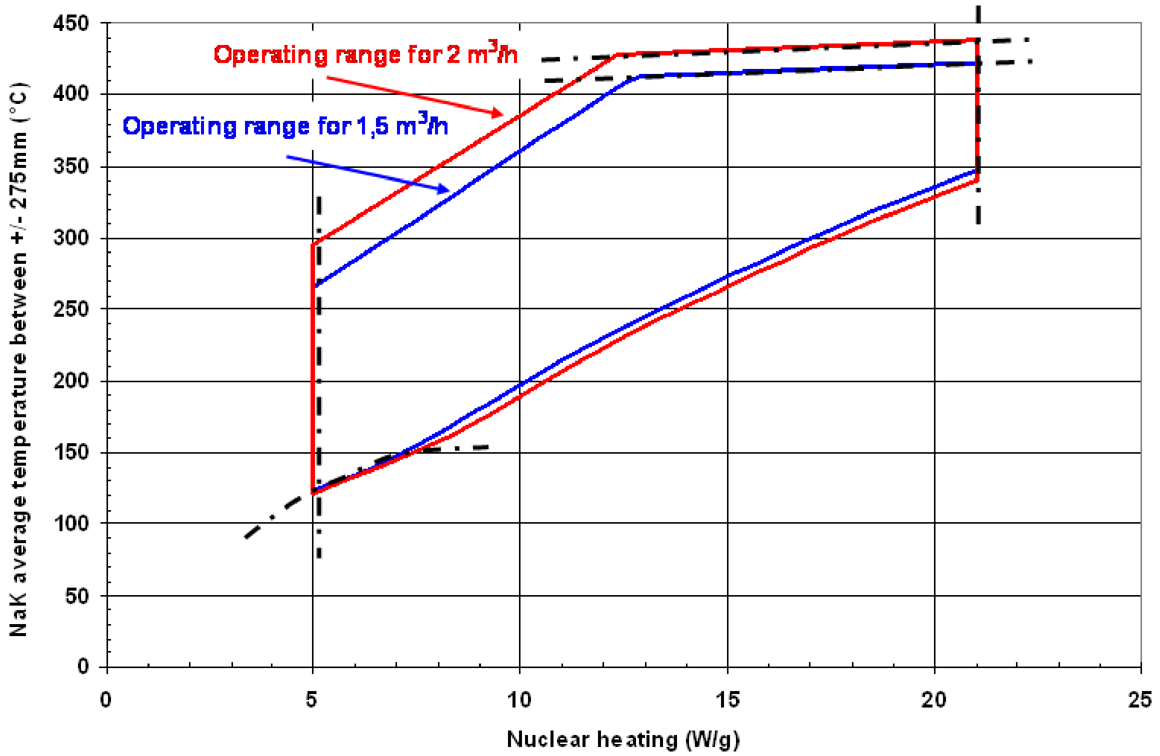

Figure 7 : Operating range for NaK flowrate of 2 m^3/h and 1.5 m^3/h

4.4 Management of temperature fluctuations

During reactor cycle, the best way to compensate small variations of sample temperature due to nuclear heating fluctuations is to control the electrical power of the heaters while keeping the NaK flowrate constant at its nominal value (balance between thermal performances and pumping performances).
Table 3 shows that fluctuation of ± 4% of nuclear heating leads to about 5℃ variation of the NaK temperature, which could be easily managed by less than a 800 W power variation of the electrical heater. In such conditions, the quality criterion is only slightly affected.

	Nuclear heating	Electrical Power	NaK average temperature	ΔT_{NaK} criterion
Reference	17.6 W/g	10 073 W	328℃	2.2 ℃
Nuclear perturbation	17.6 **- 0.7 W/g**	10 073 W	328 **- 6℃**	4.5 ℃
Elec. heater adjustment	17.6 **- 0.7 W/g**	10 073 **+790 W**	328℃	5.3 ℃
Nuclear perturbation	17.6 **+0.7 W/g**	10 073 W	328 **+4℃**	4.2 ℃
Elec. heater adjustment	17.6 **+0.7 W/g**	10 073 **-751 W**	328℃	3.8 ℃

Table 3 : Nuclear heating fluctuation for 2 m^3/h flowrate

5. CONCLUSION

The present design of CALIPSO comes from optimization between mechanical dimensioning considerations with compliance to safety rules and thermal behavior. Extensive thermal calculations were made to define its optimum operating range as a material irradiation device in the core of the Jules Horowitz Reactor.

To quantify the experimental performance of such a test device, a quality criterion of 7.5℃ on the NaK temperature difference over the sample zone has been defined. Its purpose is to keep the temperature distribution homogeneous around the samples. The study covered a large nuclear heating range (5 W/g - 21 W/g) and NaK temperature from 150℃ to 450℃. Different NaK flowrates were investigated and parameters of influence were tested.

The analysis of results lead to the main following observations :

- sample shape and type of material have a large influence on the NaK temperature level,
- it is necessary to have different lengths of heat exchanger to provide a large optimal operating range regarding nuclear heating values and NaK temperature,
- NaK flowrate has to be kept constant during the normal conditions : 1.5m^3/h to 2m^3/h is the optimal range,
- during irradiation, the best way to compensate temperature changes is to adjust the electrical power of the heaters.

Progress has been performed on the detailed design of CALIPSO and the manufacturing of an out-of-pile prototype is under way. This prototype will be used to qualify the performance of the main components and to validate the thermal assessment of such a test device toward its licensing for irradiation in the Jules Horowitz Reactor.

6. REFERENCES

(1) D. Iracane, “The JHR, a new Material Testing Reactor in Europe “, *International Symposium on Research Reactor and Neutron Science, Daejeon, Korea, April 2005*

(2) JP. Dupuy, G. Perotto, G. Ithurralde, C. Leydier, X. Bravo, “Jules Horowitz Reactor : General layout, main design options resulting from safety options, technical performances and operating constraints”, *TRTR 2005 / IGORR 10 Joint Meeting, Gaithersburg, Maryland, USA - September 12-16, 2005*

(3) S. Carassou, G. Panichi, F. Julien, P. Yvon, M. Auclair, S. Tahtinen, P. Moilanen, S. Maire, L. Roux , “Experimental material irradiation in the Jules Horowitz Reactor “, *TRTR 2005 / IGORR 10 Joint Meeting, Gaithersburg, Maryland, USA - September 12-16, 2005*

(4) D. Moulin, C. Biscarrat, S. Christin, G. Laffont, A. Morcillo, E. Pluyette, F. Rey, ” Design of a flowing-NaK experimental device for in-core irradiation in the Jules Horowitz Reactor”, *European Nuclear Society RRFM 2009, Vienna, March 22-25, 2009*

(5) RCC-MX code – ”Règles de Conception et de Construction des Matériels Mécaniques des Réacteurs Expérimentaux, de leurs auxiliaires et des dispositifs d’irradiation – Design and construction rules for the mechanical components of research reactors and irradiation devices”– *CEA (Edition 2008)*