Out-of-pile testing of the CALIPSO irradiation device for the Jules Horowitz Reactor

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ABSTRACT

The CALIPSO device is a NaK liquid metal loop for material irradiation in the core of the Jules Horowitz Reactor. A prototype for out-of pile testing was manufactured and a specific experimental facility called SOPRANO was built at the CEA Cadarache centre. Since September 2013, the qualification of the prototype over all its operating range has been carried out.
After a short recall on the CALIPSO device and its operating principle, the main results of the experimental campaigns are presented in this paper.
The electromagnetic pump showed very good time stability and reproducibility all along the campaigns to control NaK flowrate up to 0.5 kg/s.
Concerning thermal behaviour, the modularity of the heat exchanger is very efficient to enlarge the temperature operating range. For instance, the targeted 450°C NaK temperature was obtained with the shorter heat exchanger configuration. Besides, by controlling the electrical power parameters, one could flatter the NaK temperature profile in the test channel down a few degrees over the 765 mm heating length of the electrical rod.
These experimental campaigns were necessary to qualify the overall behaviour of CALIPSO and to characterize the main components. Most of the results are consistent with the expected values. The objective of reducing the thermal gradient in the flowing NaK along the sample zone has been achieved. Therefore, it confirms the adequate design of CALIPSO to perform irradiation of material samples with an accurate control of the coolant temperature conditions over a large range of heating power.

1. Introduction

Test devices in research reactors such as the Jules Horowitz Reactor, are designed to provide specific experimental conditions to study material behaviour under irradiation (1). Among them, the CALIPSO device is a Sodium-Potassium (NaK) liquid metal loop for material irradiation in the reactor core. Its design and thermal performances have been presented in previous congresses (2), (3). Two out-of-pile hard mock-ups were manufactured; one concerning the prototype of the in-core part (4) and the other one concerning the prototype of the head (5). At the same time a new experimental facility called SOPRANO was developed and built at the CEA Cadarache centre (4). Since September 2013, the qualification in realistic conditions of the prototype with NaK has been carried out. After a short recall on the CALIPSO device and its operating principle, the main results of the experimental campaigns are presented.

2. General description of CALIPSO

An important requirement for experimental conditions in test devices with a lot of samples is to keep the temperature distribution homogeneous. In the case of CALIPSO, the accurate temperature control of the samples is possible by the mean of a small in-core loop of circulating NaK. This device encloses in a confined space all the components needed to ensure a forced convection flow in the test section that is to say a pump, an electrical heater, and a so-called heat exchanger.
The overall length of the in-core test device is 6500 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 (Figure 1). It is

composed of two main parts: the containment rig and the sample-holder. The containment rig is the outer shell of the test device that houses fluids. The sample-holder is plugged into the containment rig through the circular opening situated in the upper part. It holds the material samples to be irradiated and the specific experimental instrumentation such as thermocouples, radiations sensors, pressure sensors, strain gauges, displacement transducers, etc. It is in the lower part of the containment rig, where the internal diameter is only 24 mm, that samples and instrumentation are immerged in the experimental fluid (NaK).

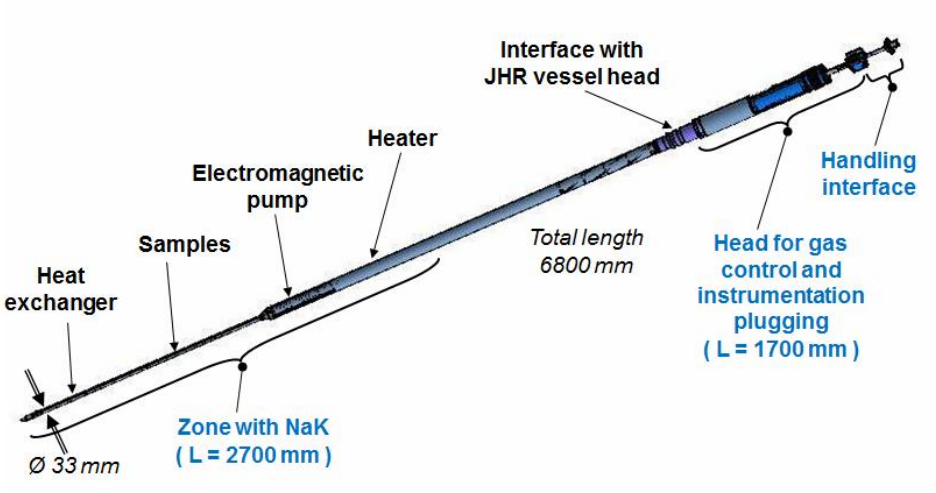

Figure 1 : General view of CALIPSO

3. Operating principle

The description of the operating principle is illustrated by a schematic view given Figure 2.
Material samples ❸ are located in the central channel of the test device in the 600 mm-long active zone of the reactor core **(A)**. Gamma and neutron radiations induce heating of materials.
A very compact annular electromagnetic pump (EMP) ❹ makes NaK flowing down around samples. It is a 500 mm-long and 78 mm-large component located in the containment rig ❶ just above the active zone.
An electrical heater ❺ is situated in the NaK above the pump. It is necessary to control the temperature operating conditions in the sample zone. Its maximum power is 18 kW over a total length of 400 mm.
Internal heat transfer between NaK counter-flows occurs through the separator shell ❼. And thermal equilibrium of the system is obtained by heat loss to the water of the reactor primary circuit **(B)** through the Helium gas gap **(C)**.
A 700 mm-long component called heat-exchanger ❻ is located at the lower part of the sample-holder ❷, below the active zone. It is designed to be configured in hot cell before irradiation in order to have the NaK flow return at a variable altitude, thus to provide a variable area of heat exchange (Figure 3).

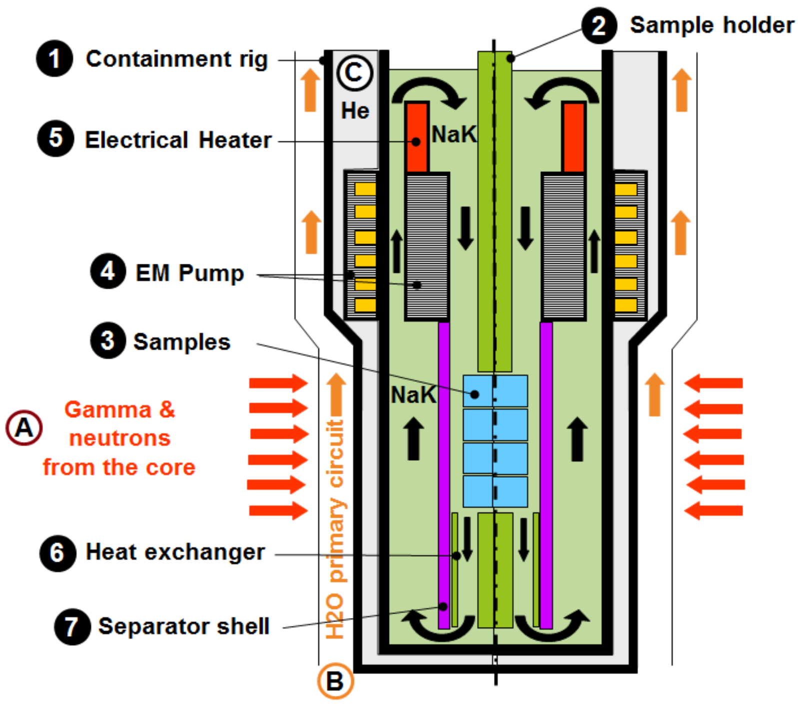

Figure 2 : Schematic view describing the operating principle

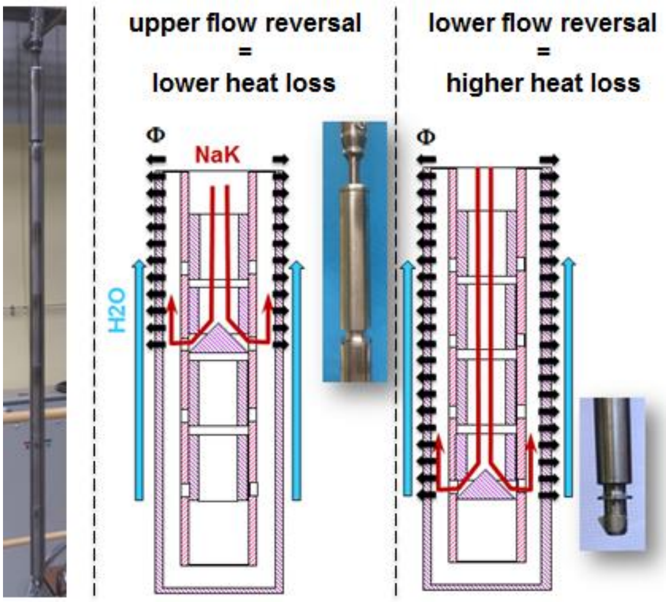

Figure 3 : Modular heat exchanger

4. The prototype of CALIPSO and the qualification facility

The prototype of CALIPSO consists in the bottom part of the actual test device. It is composed of all the components entering into the NaK loop with the same geometry (Figure 4). To simulate nuclear heating, a 765mm-long 20kW-powered electrical heating rod replaces the actual sample holder (Figure 5).

The prototype is also highly instrumented with 48 thermocouples for coolant and material temperature measurements. Pressure measurements at the inlet and the outlet of the pumping channel are effective thanks to small tubes connected to external pressure sensors.

Figure 4 : The outer flask and the electromagnetic pump on the inner flask

Figure 5 : Electrical rod with thermocouples clamped on the cladding

The SOPRANO facility is an operating platform with different components and circuits, built to perform experimental testing on the mock-up of CALIPSO and to allow operations with NaK (Figure 6).

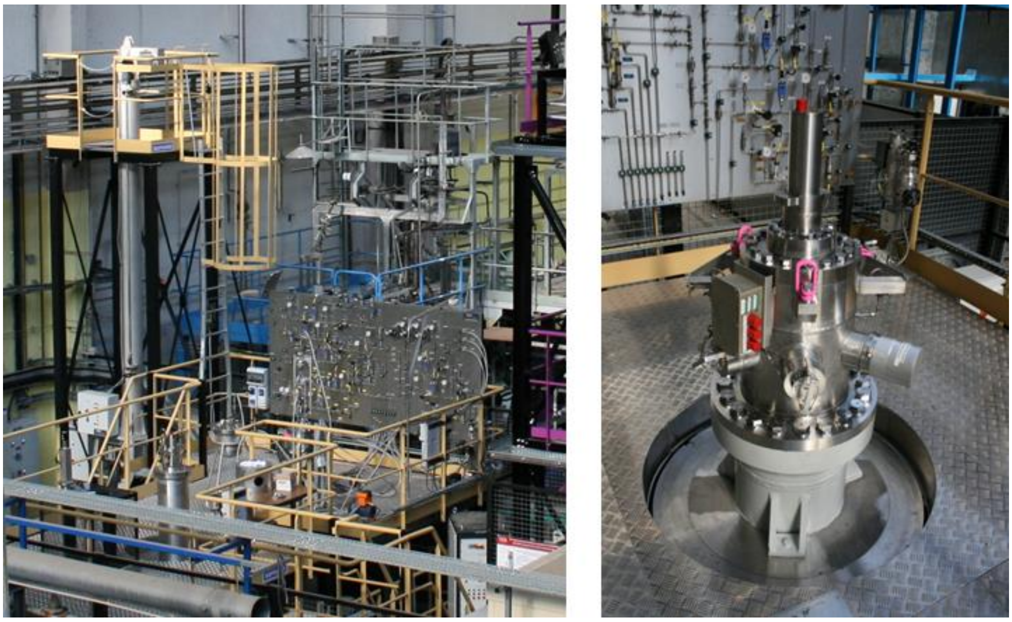

Figure 6 : Pictures of the SOPRANO facility

5. Experimental program

The first goal of the experimental program was to characterize the EMP by measuring the NaK differential pressure between the outlet and inlet of the pumping channel. This is correlated with the NaK flowrate through the total pressure drop of the integrated loop. By varying the power supply of the pump (voltage and frequency), it is possible to cover a large range of NaK flowrate.

A second goal was to evaluate the overall thermal performances of the device by changing the power supply of each electrical heater and recording all electrical parameters. Several thermocouples are immerged in the NaK and others clamped on the main components (Figure 5). Thus, a very accurate monitoring of the test device temperature is carried out during experimental campaigns. Furthermore, by changing the heat exchanger length, one can reach different operating conditions regarding pressure drops and thermal balance. Since September 2013, three heat exchanger configurations were tested corresponding to 3 specific experimental campaigns (Table 1).

Campaign #	Dates	Configuration
1	Sep.- Oct. 2013	Long-length heat exchanger
2	Jan.- Apr. 2014	Short-length heat exchanger
3	Oct.- Dec. 2014	Medium-length heat exchanger

Table 1 : Characteristics of the experimental campaigns

6. EMP characteristics

First of all, the EMP showed very good time stability all along the campaigns. As an example, Figure 7 shows a 5 hour-long steady state operation at 320°C.

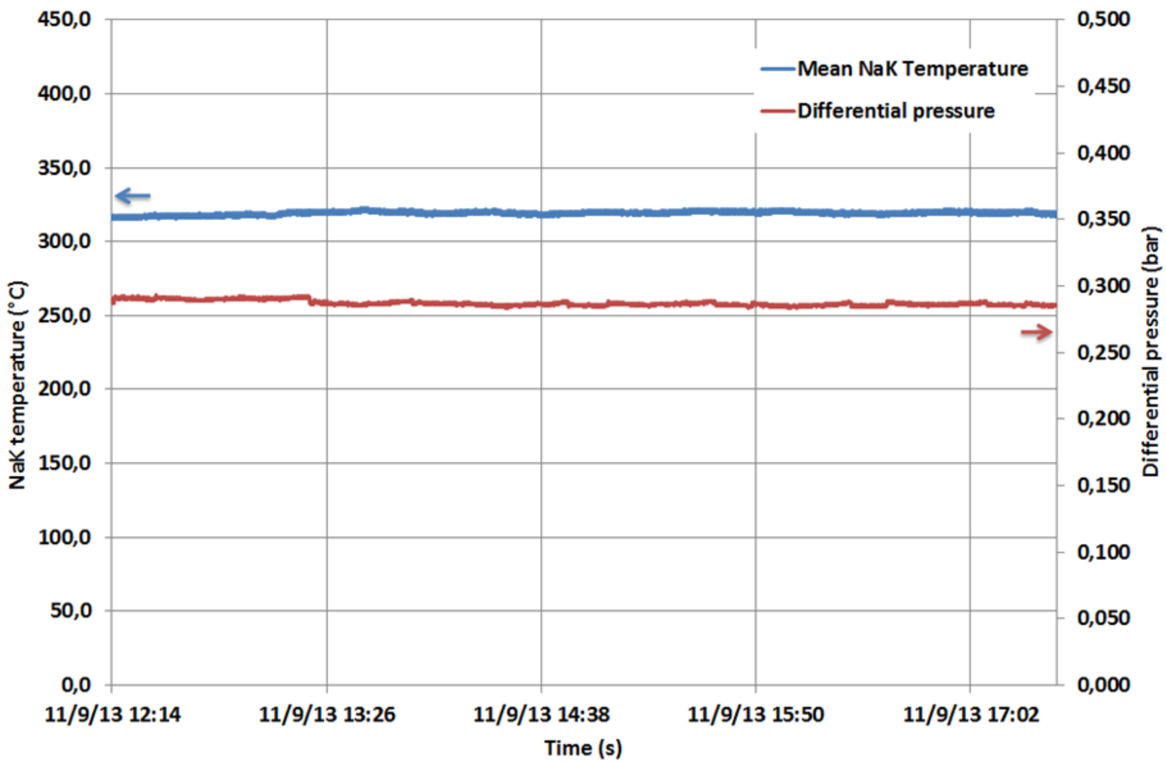

Figure 7 : Example of a 5 hour-long steady state EMP operation

Concerning pump operating characteristics in the test device, it can be noticed (Figure 8) that the differential pressure decreases while the heat exchanger length is smaller. This is obviously consistent with the change of linear pressure drop in the annular tube of the heat exchanger. Maximal load pressure is 0.9 bars. It was obtained with the long heat exchanger. Absolute uncertainty on differential measurement is ± 0.003 bar.

There is no flowrate sensor in the prototype. However flowrate can be evaluated based on the measured differential pressure and correlations from pressure drop calculations using computational fluid dynamics (CFD) software. In such a way, an estimation of flowrate absolute uncertainty is ± 0.02 kg/s. By processing data from differential pressure, it is possible to plot flowrate versus EMP power supply (Figure 9). The curves fit quite well whatever the heat exchanger configuration, and a maximal value of 0.5 kg/s can be reached.

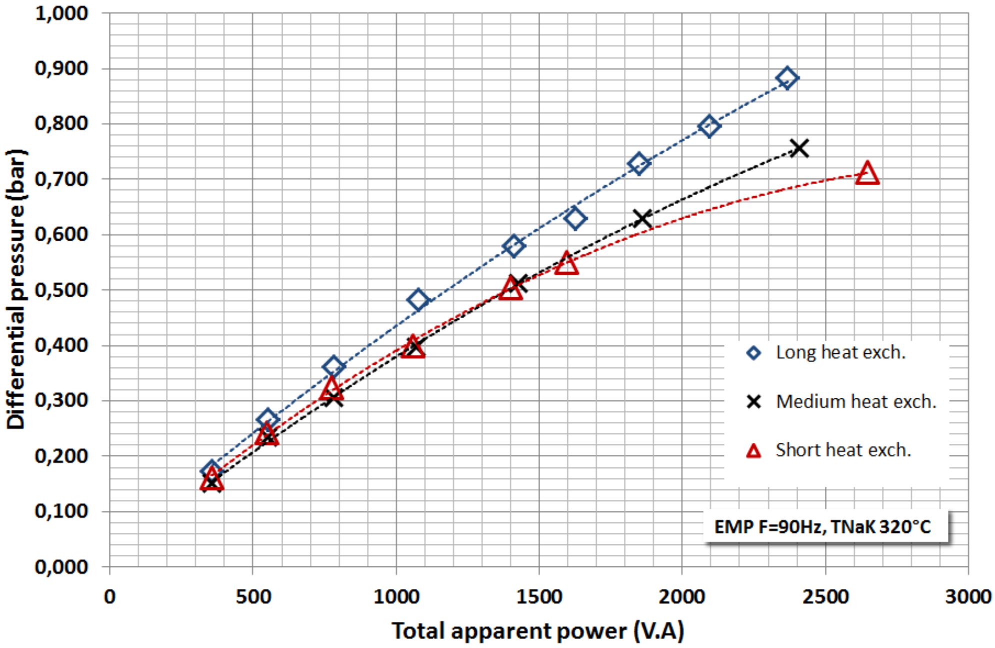

Figure 8 : Pump operating characteristics in the test device

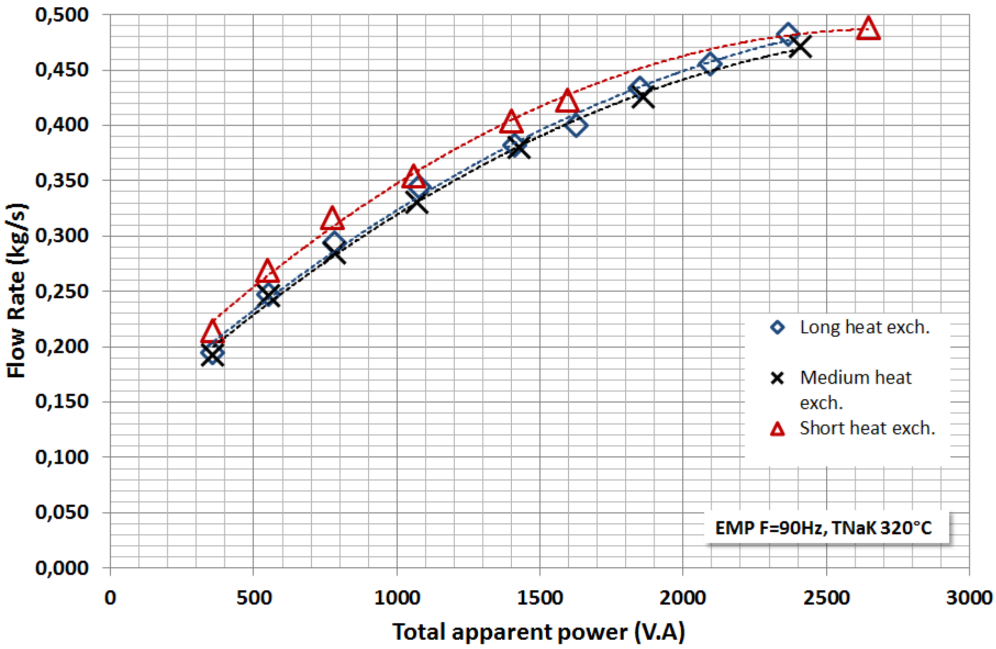

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Figure 9 : Flow rate in the test device

7. Thermal performances

Figure 10 plots maximal NaK temperature versus heating power for the three tested configurations. As expected, to reach the same temperature level, smaller heating power is necessary with the short-length heat exchanger. Thus, the 450°C maximal NaK temperature can only be obtained with this configuration while it is 350°C with the others.

However, it cannot be observed any significant difference between long length and medium length curves. The reason is not well known and an additional experimental campaign should be necessary to investigate this phenomenon.

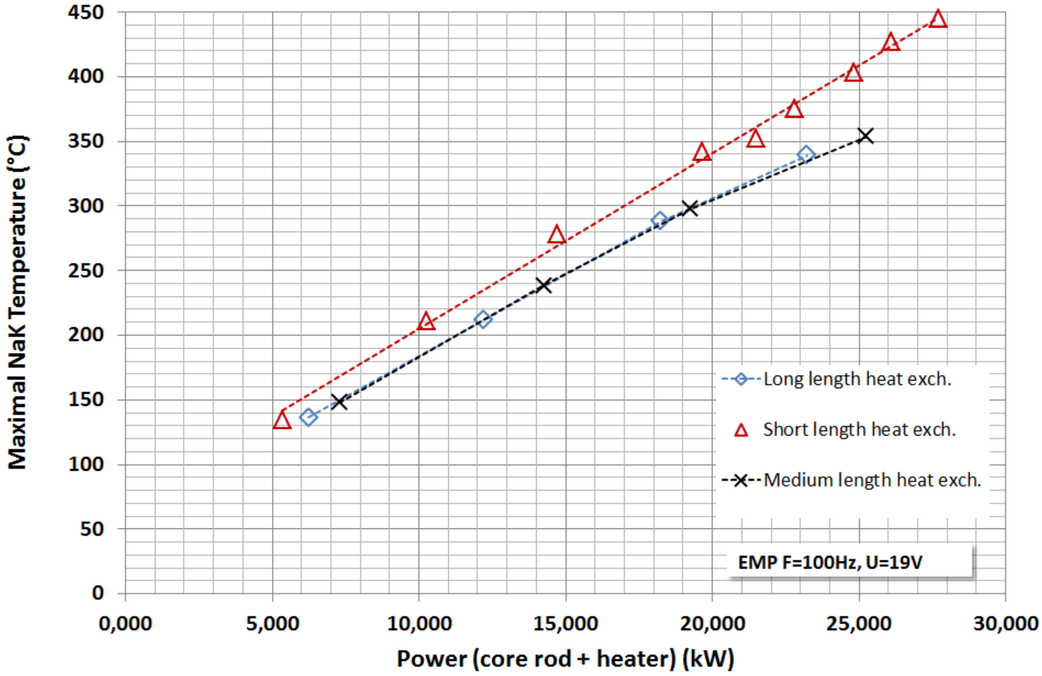

Figure 10 : Maximum NaK temperature (EMP F=100Hz, U=19V)

Calculation showed that the ability of reducing the thermal gradient in the flowing NaK along the sample zone could be controlled by the power of the electrical heater in regards of the nuclear heating in the sample zone (3).

In the prototype, the thermal gradient is evaluated by the differential temperature measured between thermocouples clamped on the rod upward and downward the heating zone. Given a NaK flowrate value and a rod power level, the electrical heater input could be adjusted to have the thermal gradient close to zero. The optimum power sharing is roughly 1/3 electrical heater and 2/3 heating rod. Besides, in such a condition, the NaK temperature profile in the test channel flattened down a few degrees over the heating zone. Figure 11 gives an example of power sharing impact on NaK temperature profile.

Sensitivity tests to NaK flowrate variation and rod power changes were carried out to check the loop feedback controller on the electrical heater. Results show good stability of NaK temperature and only small deviation from the optimum temperature profile.

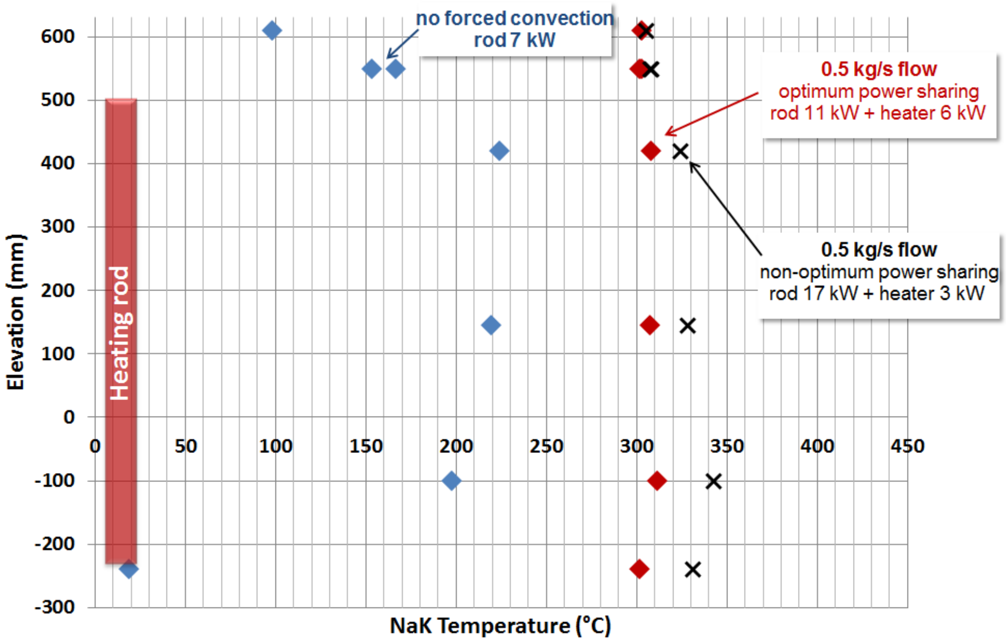

Figure 11 : Impact of power sharing on NaK temperature profile

8. Conclusion

These experimental campaigns were necessary to qualify the overall behaviour of CALIPSO and to characterize the main components. Most of the results are consistent with the expected values. The EMP showed very good time stability and its operating characteristics allowed reaching the 0.5 kg/s targeted flowrate. The modularity of the heat exchanger is quite efficient to enlarge the temperature operating range. The objective of reducing the thermal gradient in the flowing NaK along the sample zone has been achieved. Therefore, it confirms the adequate design of CALIPSO to perform irradiation of material samples with an accurate control of the coolant temperature conditions over a large range of heating power.

Future experimental work will focus on component reliability under long operating time. Concerning the design of the actual irradiation device for the Jules Horowitz Reactor, some improvements are necessary to take into account feedback from the manufacturing and the testing of the CALIPSO prototype.

9. References

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