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CAREM: Argentina’s innovative SMR

First concrete was poured in February for the prototype of the domestically-designed CAREM 27 MWe small modular reactor. This article gives an overview of the main thermal-hydraulic features of the natural circulation, self-pressurized, integral reactor. By Christian Marcel, Darío Delmastro, M. Celeste Magni and Osvaldo Calzetta.

Caroline Peachey May 14, 2014

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In recent years, small modular reactors have attracted attention because they can meet the needs of emerging electricity markets. They use a proven technology together with novel designs, including new engineering solutions relying on passive features. Passive safety features do not require outside power input to work, instead depending only on physical laws.

An example of this is the CAREM-25 reactor, which is an Argentine project designed to deliver 27 MWe with minimum operator feedback control. This nuclear plant is an indirect-cycle reactor with distinctive features that greatly simplify the design, improving safety. Its primary circuit is fully contained in the reactor vessel (eliminating the possibility of a loss of coolant accident), it has no cooling pumps (since natural convection drives the primary flow) and pressurization is achieved by balancing vapour production and condensation in the vessel (thus eliminating the need for an active external subsystem). The CAREM-25 design reduces the number of sensitive components and potentially risky interactions with the environment.

This article describes the most important thermal-hydraulic phenomena, showing how the CAREM-25 behaviour differs from existing water-cooled reactors. Some of the most important phenomena are self-pressurization, natural circulation, flashing, subcooled boiling, density wave instabilities, neutronic feedback and condensation. The CAREM-25 concept was presented in 1984 and was one of the first designs in the present new generation of reactors. It has been recognised as a ‘near-term deployment’ reactor by the Generation IV International Forum (GIF).

Numerous researchers have in the past made numerical and experimental studies of natural circulation systems. However, none of those studies looked at this case of a self-pressurized system. Different small integrated reactor designs exist, some of which are (partially) cooled by natural circulation low-quality flows, whose phenomenology has been discussed elsewhere. What makes CAREM-25 different that it does not have any active device controlling the system pressure. For this reason, the linked phenomena in operation in the plant cause it to behave differently to traditional LWRs (including the referenced designs). Such a difference has important consequences for the reactor thermal-hydraulics.

CAREM-25 reactor design

The entire CAREM-25 is considered an integrated reactor: its high-energy primary system (core, steam generators, primary coolant and steam dome) is contained inside a single 11m high, 3.5m-diameter pressure vessel. Primary cooling flow is achieved by natural circulation, which is induced by placing the steam generators above the core.

The right-hand side of Figure 1 shows natural circulation of the coolant in the primary system. Water enters the core from the lower plenum. After being heated, the coolant exits the core and flows up through the chimney to the upper steam dome. In the upper part, water leaves the chimney through lateral windows to the external region. It then flows down through modular steam generators, decreasing its enthalpy.

The coolant exits the steam generators and flows through the downcomer to the lower plenum, closing the circuit. At steady-state conditions, the driving forces created by the density differences along the circuit are balanced by the friction and form losses, so there is an adequate flow rate in the core. The coolant there is an adequate flow rate in the core. The coolant also acts as a neutron moderator.

Self-pressurization of the primary system in the steam dome is the result of the liquid-vapour equilibrium, so the heaters used in conventional PWRs are eliminated. The large vapour volume in the RPV also helps damp pressure perturbations. The self-pressurization means that bulk temperature at the core outlet is at saturation temperature at primary pressure.

Physical phenomena

Individually, the physics involved in self-pressurization, flashing, natural circulation, condensation, density wave instabilities and neutronic coupling in the reactor are well known. In combination, however, they give rise to numerous feedback loops that influence the reactor dynamics, creating novel situations that are potentially destabilizing and therefore need to be investigated in depth. The phenomena and their consequences are described in detail below.

In the CAREM-25 reactor the steam quality is very low and therefore the largest contribution to the momentum balance is single-phase buoyancy forces. This is shown in simplified diagrammatic form on the left of Figure 1.

Some vapour needs to be created inside the RPV in order to have a constant system pressure. This constraint fixes the core outlet temperature close to the saturation value. Assuming there is no carry-under of bubbles in the downcomer, the vapour created in the hot leg is condensed before entering the cooling devices [carry-under of bubbles in the downcomer and devices [carry-under of bubbles in the downcomer and carryover of water to the turbine requires analysis that is neither simple or straightforward; it goes beyond the scope of this article]. Condensation takes place in the upper part of the reactor vessel and is a direct consequence of the heat losses and the interaction between the vapour and cold structures in the steam dome, such as those from the reactivity control mechanism.

The steady state energy balance for the entire circuit yields:
QNuc = QSG + QCond

where QSG is the power extracted by the cooling devices (that is, the steam generators) and QCond the power related to vapour condensation phenomenon.

In operational conditions (QNuc >>QCond), when the power level is decreasing while all other parameters are kept constant, the core mean enthalpy approaches saturation value, so that the core is hotter at low power levels than at nominal conditions. This counter-intuitive result is related to the fact the core inlet enthalpy is not a controlled variable as in conventional reactors.

> "Natural circulation is enhanced in this type of reactor by using a high chimney."

Some vapour is created in the core (although the core exit vapour quality is practically zero) and a certain amount of vapour is produced by flashing in the chimney. As shown in Figure 1, density differences between the cold and hot legs cause the water to flow without using pumps. Natural circulation is thus enhanced in this type of reactor by using a high chimney. As the heated coolant flows upwards, the hydrostatic pressure falls, so the saturation temperature decreases. When the saturation enthalpy becomes equal to the (constant) fluid enthalpy in the chimney, flash-boiled vapour appears (see Figure 1). This ex-core boiling increases as the reactor pressure decreases, since at low pressure the saturation enthalpy depends on the axial position. In CAREM-25 flashing is crucial for stability studies when the reactor is starting up (that is, at low pressure) and at nominal conditions.

The vapour produced by flashing enhances the self-pressurization of the system. If the vapour production rate is greater than the condensation rate, the system pressure will increase and the flashing effect will diminish, helping to keep the pressure constant. Vapour production in the chimney directly affects the gravitational pressure drop over this section, so the Type-I feedback mechanism is amplified by void flashing.

Studying uncertainties

The uncertainties relating to the prediction of the resulting coolant mass flow rate need to be carefully studied. Two extreme cases might occur.

In the first case, the total friction in the system might be overestimated and thus friction in reality could be much smaller than estimated. It is well known that two of the crucial parameters influencing the critical heat flux (CHF) are the local quality χ and the mass flux G flowing through the channel. The CAREM-25 reactor operates in a particular region of the critical heat flux qcr versus the mass flux G curve, which is characterized by a decrease in qcr when increasing G. In order to clarify this behaviour, Figure 2 is built, for CAREM-25 conditions, by using 1986 AECL-UO Critical Heat Flux Lookup Table, Heat Transfer Engineering 7 (1), 46-62, by DC Groeneveld, S.C. Cheng and T. Doan.

If the real friction in the system is lower than the estimated value, both the mass flux and the mean quality increase (that is, the mean quality becomes less negative), reducing the thermal margin. For this reason it is very important to fix a maximum mass flow rate in the reactor.

In the second case, the total friction in the system might be underestimated, which would imply that the real mass flow rate is much smaller than expected. This might mean the steam generators need to work beyond their design limits, as they are unable to evacuate power as required.

From this simple analysis it is clear that, for a given power, the mass flow rate must remain within a certain range to avoid any undesired consequences. In particular, it must not exceed the design value, in order to preserve the thermal margin.

Despite this limitation, the fact that CAREM-25 operates in such a particular region of the qcr vs. G curve has certain benefits in accidental conditions. When the reactor is SCRAMMED, the mass flux decreases, since the power is considerably reduced. As decreases, since the power is considerably reduced. As a result the reactor starts operating in a region with a higher critical power, which helps increase the thermal margin. The same argument can be made if the coolant level accidentally decreases in the RPV.

Reactor stability

> "The system might be susceptible to density wave oscillations (DWO), and in particular so-called Type-I instabilities."

Since low thermodynamic quality natural circulation drives the primary flow in the reactor, the system might be susceptible to density wave oscillations (DWO), and in particular so-called Type-I instabilities. This instability mechanism becomes dominant in natural circulation reactors operating at low power and pressure conditions, or when the flow has low thermodynamic quality. Under these conditions, the mass percentage of steam at the core outlet becomes very small. For small flow qualities, the volumetric amount of steam (the void fraction) increases very rapidly as a function of the flow quality. A small reduction in the core inlet flow then leads to a large increase in the volume of steam produced at the core outlet.

In a natural circulation reactor, this causes a low-density wave to travel through the chimney. This enhances the driving head, and the inlet flow will therefore increase. Then the opposite process occurs, and the void fraction in the chimney decreases.

Consequently, the driving head becomes smaller, and the flow rate will decrease. This completes one cycle of a Type-I oscillation. The transit time of the voids through the chimney is the main time-constant governing this type of DWO. For this reason, we should consider the stability performance of the reactor.

In order to discuss the CAREM-25 stability performance, a stability map obtained with a dedicated linear model at constant pressure and for a wide range of conditions is presented in Figure 3. The stability boundary is shown, with two more lines that correspond to cases in which the two-phase boundary is located in the core outlet and the chimney middle.

As can be observed, under a certain condensation power, for which the boiling limit λ is outside the core, the system shows a significant increase in the amplification factor. This occurs when, without core boiling, enthalpy outside the core is higher than the saturation enthalpy at the chimney outlet, producing vapour by means of flashing. The presence of vapour in the hot leg increases the buoyancy force. The higher the void fraction, the lower the average density in the hot leg and thus the higher the buoyancy force.

If the boiling limit λ is located in the chimney, the sensitivity of the buoyancy force to changes in the coolant enthalpy increases. This is because a slight perturbation in the core outlet enthalpy causes a large change in λ, which in turn causes a large variation in the buoyancy force. This tends to destabilize the system, decreasing the stability performance when is located between the chimney middle and the core outlet. As a result, when the system is unstable it can be stabilized by either increasing or decreasing QCond. The lower QCond is, the closer is regarding the chimney outlet. Therefore, when the system is unstable, by lowering QCond the two-phase region becomes smaller, reducing the void fraction contribution in the buoyancy force; as a result, it reduces its relative sensitivity. Thus, the oscillations are more efficiently damped, creating a new stability area.

The effect of the neutronic feedback on the system dynamics can be summarized as follows:

- One of the most important effects is due to coolant density changes. Where there is a constant heat flux, an increase in the core flow is followed by an enthalpy decrease at the channel outlet and, consequently, an increase in the coolant average density at that point. Because the reactivity coefficient due to coolant density r is positive there is an injection of reactivity. Then the fission power increases, which in turn increases the enthalpy at the core outlet. This tends to balance the thermal hydraulic effect, stabilizing the system.
- In addition, the neutronic feedback has a faster response than a Type-I instability mechanism. This is because a change in the average coolant density affects the nuclear core power before the arrival of the enthalpy front to the chimney outlet. This reduces the associated phase delay. This phenomenon has a stabilizing effect in the low frequency oscillations that occur in the CAREM-25. The effect of the core dynamic has a stabilizing effect on the unstable region induced by flashing phenomenon, particularly at relatively high QCond values, when the two-phase boundary is located in the core.

In summary, as a result of competing effects, the Type-I unstable region is limited to cases in which the two-phase boundary limit is located within a region between the core outlet and the chimney middle.

> "The results obtained so far regarding the CAREM-25 reactor stability performance are positive"

The results obtained so far regarding the CAREM-25 reactor stability performance are positive, since they show a large region within which the system can be operated with sufficient stability margins. It should be noted that the margin may be considerably improved by slightly increasing the condensation power at the dome. In this way, the reactor operational point can be tuned, optimizing its stability performance.

The subcooled boiling effect

The subcooled boiling effect is expected to have a stabilizing effect in the system. This is explained by the fact that the main destabilizing mechanism in CAREM-25 is density waves travelling through the chimney section, that is, Type-I. In such conditions the increase of the void fraction within the reactor core tends to increase the feedback dynamics due to coolant density variations, which has a stabilizing effect. (When there is a slight change in the two-phase flow within the core, there is a different neutron moderation rate and therefore this affects power production. Such a change also affects the two-phase flow characteristics.) This reasoning agrees well with results found in literature. Moreover, even when operating in the linearly unstable region, the resulting oscillations have a relatively small amplitude. This is oscillations have a relatively small amplitude. This is explained by the fact that the (destabilizing) two-phase buoyancy term in the momentum equation is considerably smaller than the (non-destabililzing) single-phase buoyancy term.

In the CAREM-25, the coolant from the secondary system flows through helically-coiled tubes located inside the steam generators. The coolant goes from a subcooled liquid state to superheated vapour as it passes through the tubes. As a result, instabilities due to density waves are likely to occur in the secondary side of the SGs. In addition, different heat transfer mechanisms within the SGs determine the axial heat transfer between the coolants from the primary to the secondary side. Due to the inherent complexity of such phenomena an analytical approach was preferred to investigate the system's stability performance. A nodal linear model was developed to model the stability of the helically-coiled tubes in realistic conditions. The model includes friction, acceleration, inertia and gravity effects in each region of the tubes – the subcooled liquid region (preheating zone), boiling region (evaporation zone) and vapour region (superheating zone).

Because the heat transfer mechanisms vary considerably from region to region, the axial power profile in the SG tubes is not uniform. Clearly, this feature is very important in determining the stability of the tubes, since it affects the phase shift of the feedback loops that are the basis of the density wave instability mechanism. For this reason, the model allows representation of arbitrary power profiles for each of these regions. Figure 5 shows schematically the distribution of power that would be expected when the distribution of power that would be expected when the SG operates at nominal conditions.

In order to emphasize the important changes in the lengths of each of the zones (preheating, boiling and superheating) occurring when varying the interchanged power in the SG tubes, Figure 5 was constructed. It shows that when the power decreases, the preheating zone tends to shrink. This implies that the saturation condition may reach locations too close to the inlet of the helically-coiled tubes and therefore needs to be avoided. This effect limits the minimum operational power of the SGs.

The stability results of the SG tubes are presented in Figure 6. It shows the minimum value of the inlet restriction that stabilizes the system at each operational condition. As can be noted, the lower the power, the larger the value of ki, which is a dimensionless value of the pressure drop caused by this restriction, divided by the kinetic energy. In other words, the system is less stable at low power conditions. This result agrees with an increase of the relative value of the destabilizing pressure drops produced in the boiling and superheating regions.

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