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NATURAL CIRCULATION SYSTEMS: ADVANTAGES AND CHALLENGES - I

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on

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by

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KEY WORDS

Natural circulation, Thermosyphon, Natural convection loops and Passive cooling systems

LECTURE OBJECTIVES

Natural circulation loops transport heat from a source to a sink without the aid of fluid moving machineries. This lecture briefly explains the principle of working of a natural circulation system, its various advantages and applications in nuclear and other industries. The major challenges to be overcome before the wide acceptance of natural circulation as the normal mode of coolant circulation in nuclear power reactors are briefly described. Classification of NCSs and the terminologies commonly encountered in natural circulation systems are also briefly explained.

1. INTRODUCTION

In general, a heat source, a heat sink and the pipes connecting them form the essential hardware of a natural circulation system. The pipes are connected to the source and sink in such a way that it forms a continuous circulation path. When the flow path is filled with a working fluid, a natural circulation system is ready where fluid circulation can set in automatically following the activation of the heat source under the influence of a body force field like gravity. With both the source and sink conditions maintained constant, a steady circulation is expected to be achieved, which can continue indefinitely if, the integrity of the closed loop is maintained. The fluid circulation is the result of buoyancy forces, which in turn is the result of the density differences thermally induced by the transport of heat from the source to the sink. Usually, the heat sink is located above the source to promote natural circulation. Such loops in which the fluid circulation is caused by the thermally induced buoyancy force are also known as natural circulation loops, thermosyphon loops or natural convection loops.

The primary function of a natural circulation loop (NCL) is to transport heat from a source to a sink. The main advantage of the natural circulation system is that the heat transport function is achieved without the aid of any fluid moving machinery. The absence of moving/rotating parts to generate the motive force for flow makes it less prone to failures reducing the maintenance and operating costs. The motive force for the flow is generated within the loop simply because of the presence of the heat source and the heat sink. Due to this natural circulation loops find several engineering applications in conventional as well as nuclear industries. Notable among these are solar water heaters, transformer cooling, geothermal power extraction, cooling of internal combustion engines, gas turbine blades, and nuclear reactor cores. Other novel applications include low velocity corrosion studies where uninterrupted flow for long periods (of the order of years) is required and for heat dissipation by the so called ‘liquid fins’ (Madejski and Mikielewicz (1971)). Emerging new fields of application are computer cooling, and in the study of deterministic chaos.

2. BRIEF REVIEW OF APPLICATIONS OF NC

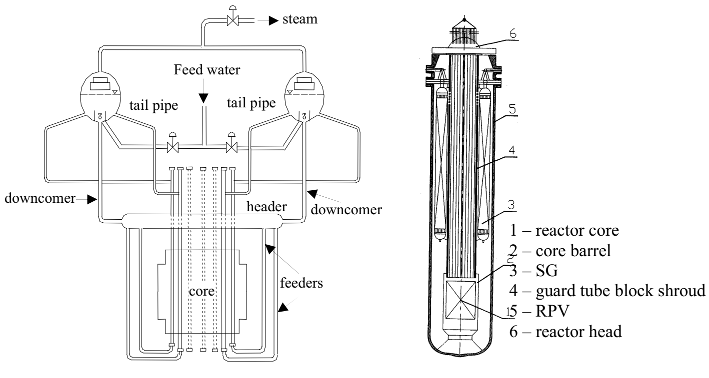
It is difficult to pinpoint when the commercial utilization of NCSs as heat transport devices began. First large-scale use of these systems appears to have been in the automobile industry to cool the engine block. With the advent of internal combustion engines of high compression ratio, their use in the automobile industry ceased practically in the 1940s (Japikse(1973)). However, NCSs have found other applications in the chemical and power generation industries. Thermosyphon reboilers are extensively used in the chemical process industries. Many fossil-fuelled power plants of low and medium capacity use natural circulation boilers (NCB). To the author's knowledge NCBs up to 660 MWe rating are in operation today. An example is the Mount Piper plant in Central West Region of New South Wales in Australia. While deploying NCBs, no concession is given with regard to the thermal performance. At the same time NCBs have less maintenance and operating cost compared to assisted circulation (forced circulation) boilers. Due to this, it is not uncommon for plants with ratings greater than 900 MWe to go for 2 or 3 NCBs rather than assisted circulation boilers.

2.1 Review of Application of NCSs in the Nuclear Industry

In the nuclear industry, NC based steam generators are extensively used in PWRs, PHWRs and VVERs. Natural circulation based steam generators of rating around 1000 MWt or more are in common use today. Natural circulation systems are also employed in nuclear industry for decay heat removal, post accident containment cooling and for cooling of radioactive waste storage facilities. Of particular concern to us is the application of NC systems in nuclear reactor core cooling. NC systems are extensively used in shutdown heat removal and post accident heat removal. Nuclear reactors continue to generate heat even after shutdown due to the decay of radioactive fission products and this heat has to be removed to maintain fuel temperatures within safe limits as was demonstrated by the TMI-2 accident. In view of this almost all nuclear power reactors are designed to remove decay heat by natural circulation in the event of a complete loss of pumping power (CLOP). A few small sized nuclear power reactors like Humbholdt Bay, Dodewaard and VK-50 demonstrated successfully the feasibility of operation with natural circulation as the normal mode of core cooling. Today natural circulation is beginning to be seriously considered for cooling of core under normal operating conditions in many innovative nuclear reactors.

2.1.1 Review of NCSs in Innovative Reactors

The NCSs used in innovative nuclear reactors (INRs) for normal core cooling, decay heat removal and other cooling systems are briefly reviewed in this section.



(a) AHWR (b) BF500 SKDI SCR

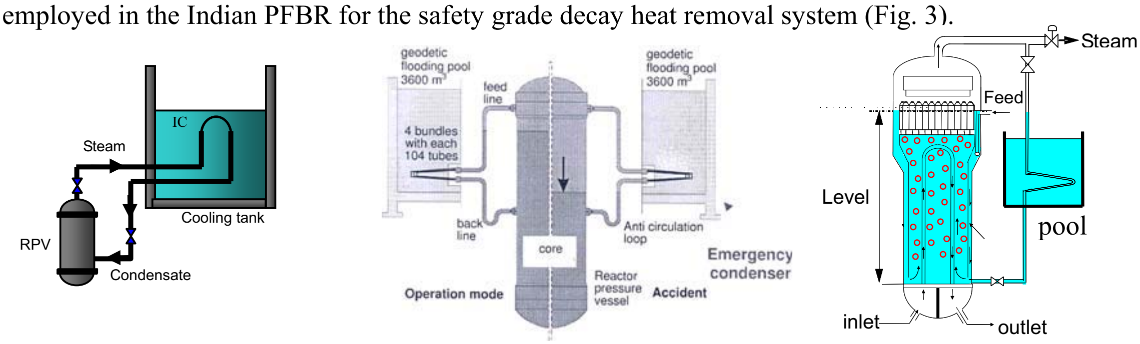
Fig.1: Some NC based Reactors

2.1.1.1 INRs with NC as the Normal Circulation Mode

Several innovative reactor concepts with NC mode have already been proposed. These include low pressure heating reactors (Dazong et al. (1993) and Samoilov and Kurachenkov (1997)), PWRs (CAREM and ABV), BWRs (AHWR, ESBWR and VK-300), supercritical reactors (SCRs) (examples are BF500 SKDI and CANDU-X-NC) and liquid metal cooled FBRs (LFR (Allen and Wade (2002)) and STAR-LM (Spencer et al. (2000))). These come in all construction types, i.e. pressure tube type (CANDU-X-NC (Bushby et al. (2000) and AHWR (Sinha and Kakodkar (2006) (Fig.1a)), vessel type (ESBWR and VK-300) and integral type (CAREM (Delmastro, (2000)), ABV, STAR-LM, LFR, BF500 SKDI (Silin et al. (1993)) (Fig. 1b)). Integral type is the most popular among these and is found in all reactor types i.e. PWR, SCR and LFR.

2.1.1.2 NC Based Decay Heat Removal Systems

Several advanced designs employ immersed heat exchangers for decay heat removal. Schematics of such system are shown in Fig.2. Most systems in this category have a mission time which is determined by the heat sink capacity and can vary from 30 minutes to 72 hours. The system can be attached to the steam generator instead of the core as has been done in SWR-1000 and PHWR-700. Besides, the heat exchanger tubes can also be V-shaped instead of the vertical U-tubes. The mission time is limited by the inventory of the cooling water contained in the pool. The Isolation condenser system employed in ESBWR and AHWR are examples of such systems. In certain cases the ultimate heat sink is the atmosphere or the sea in which case the mission time is unlimited. Such a system is employed in the Indian PFBR for the safety grade decay heat removal system (Fig. 3).



(a) Isolation condenser in BWR (b) SWR-1000 (c) PHWR-700

Fig. 2: DHR system with immersed heat exchangers

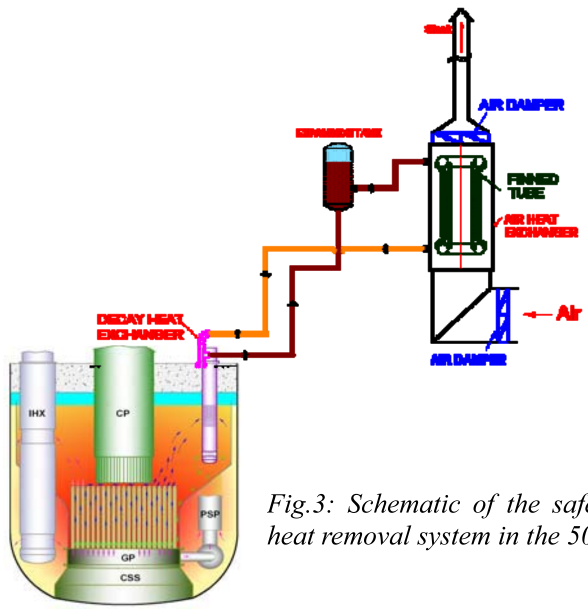
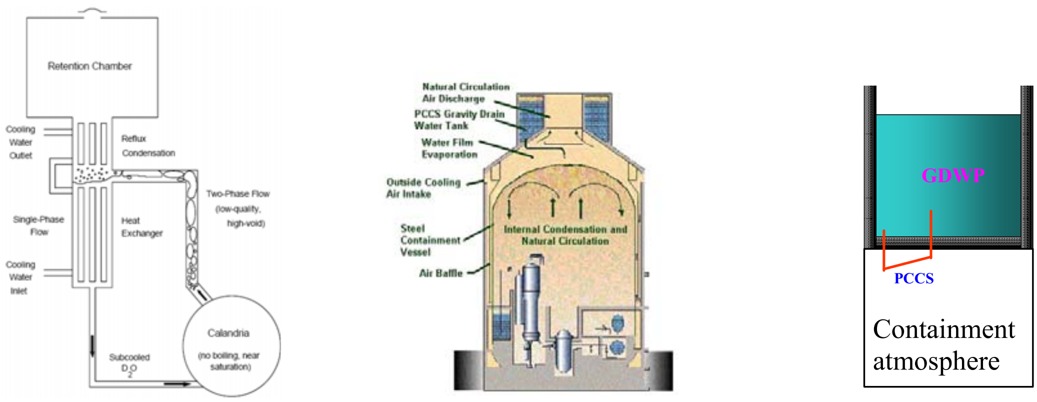


Fig.3: Schematic of the safety grade decay heat removal system in the 500 MWe PFBR

2.1.1.3. Other NC Based Systems

Apart from core cooling, natural circulation systems are also proposed for moderator cooling, containment vessel and containment atmosphere cooling (Fig.4). Besides, NCSs are also used for non-cooling applications such as passive shut down of reactors (Fig. 5). Typical examples are the flashing driven NCS proposed for moderator cooling in advanced CANDU reactors, the passive containment cooler (PCC) in AHWR and ESBWR, the passive shutdown systems in PIUS (Boyack, et al. 1995) and SWR-1000 reactors using the density lock concept and the passive pressure pulse transmitter respectively. NC of air with the atmosphere as the ultimate heat sink is used to cool the guard vessel in STAR concept (Spencer et al. (2000)) and the steel containment vessel in the AP-1000 reactor (Cummins et al. (2003)).

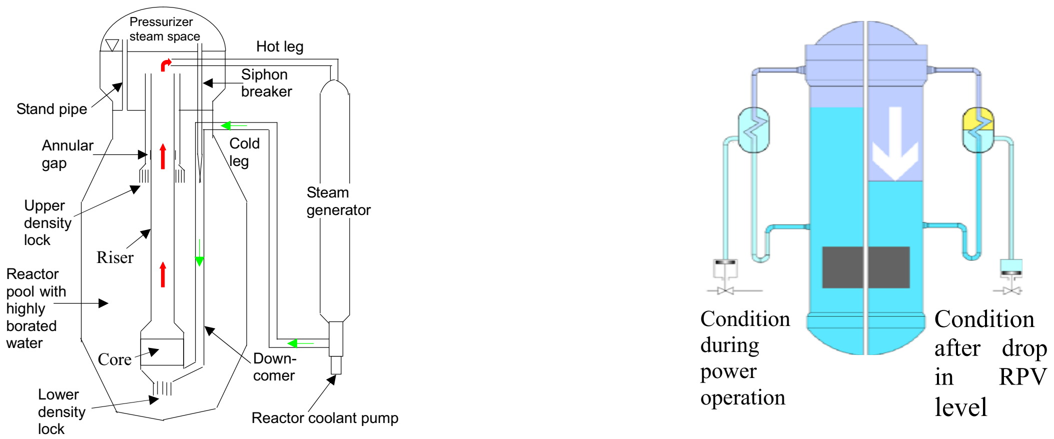


(a) Moderator cooling in CANDU reactor

(b) Containment vessel cooling system in AP-1000 [14]

(c) PCCS in AHWR

Fig. 4: Some innovative NCSs



a) Schematic of PIUS reactor

b) Passive pressure pulse transmitter in SWR-1000

Fig. 5: NCS in PIUS and AHWR

3. WORKING PRINCIPLE OF NATURAL CIRCULATION SYSTEMS

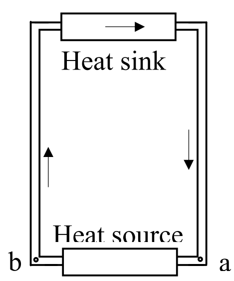


FIG. 6. A simple natural circulation system

Before we move further, let us illustrate the working principle of natural circulation with reference to the simple uniform diameter rectangular loop with adiabatic pipes shown in Fig. 6. At the source, the fluid absorbs heat becomes lighter and rises. At the sink the fluid rejects heat becomes heavier and sinks thus establishing a circulation. If the source and sink conditions are maintained constant, a steady state is expected to be achieved when the heat absorbed at the source is equal to the heat rejected at the sink. Under steady conditions we assign a density of ρ_h to the vertical leg with upward flow and ρ_c to the other vertical leg with downward flow. Now we can obtain the hydrostatic pressure, p_a and p_b at the stations 'a' and 'b' located at the extremes of the bottom horizontal leg as:

$$p_a = \rho_c g H \tag{1}$$

$$p_b = \rho_h g H \tag{2}$$

Where H is the loop height and g is the acceleration due to gravity. Clearly, since $\rho_c > \rho_h$, $p_a > p_b$ leading to a pressure difference between stations 'a' and 'b' which is the cause of the flow. At steady state, the driving pressure differential is balanced by the retarding frictional and accelerational forces, thus providing a basis for the estimation of the induced flow. What is more important to us is that this induced flow is unidirectional and while it passes through the source it absorbs heat and rejects it while flowing through the sink thus enabling transfer of heat from the source to the sink. In this function, it is indistinguishable from forced flow. It is easy to note that the induced pressure differential and hence the flow is enhanced by the loop height and the density difference between the two vertical legs.

4. ADVANTAGES OF NATURAL CIRCULATION

4.1. Elimination of Pumps

The most apparent economic advantage of NCSs is the elimination of the circulating pumps. Elimination of the primary circulating pumps not only reduces capital, operating and maintenance costs but also eliminates all safety issues associated with the failure of the circulating pumps.

4.2. Better Flow Distribution

Commercial power plants, be it nuclear or fossil-fuelled, use a large number of parallel heated channels connected between an inlet an outlet header/plenum. All analyses are carried out assuming the pressure to be uniform in the inlet headers so that the pressure drop across the parallel channels is constant. However, use of pumps cause maldistribution of pressure in the headers leading to maldistribution of flow in the parallel channels. Operating experience with fossil-fuelled NCBs suggest that the problem is eliminated or an order of magnitude less.

4.3. Flow Characteristics

In a NCS, the flow increases with power, where as in a forced circulation two-phase system the flow decreases with increase in power. This has specific advantages in steam generating power plants. In fossil-fuelled power plants, this is cited as one important aspect for the preference of NCBs over the assisted (same as forced) circulation boilers. In forced circulation BWRs, the necessity of variable speed drives essentially arises from this fact. Although, the boiler tubes are designed for a specified power, the steam production rate of individual boiler tubes are far from uniform due to the maldistribution of power. In fossil fuelled power plants, the flow characteristic of NCBs also enables them to operate with nonuniform power distribution without causing CHF. Similar conditions in an assisted circulation boiler can cause CHF.

4.4. Safety Aspects

Since NC is based on a natural physical law, it is not expected to fail like the fluid moving machineries such as pumps. This aspect of NC has enabled its application in many systems requiring long term uninterrupted flow. In all current designs of nuclear power reactors, NC is a backup for the removal of decay heat in the event of a pumping power failure. Apart from this, the driving force for natural circulation systems is somewhat low compared to forced circulation systems. As a result, the power ratings of natural circulation systems are comparatively low. Consequently, systems of same power rating are larger in volume leading to a lower power density. Large volumes and low power densities make all transients sluggish.

4.5. Simplicity

Because of the necessity to minimize pressure losses to enhance flow rates, designers of NCSs tend to eliminate all unnecessary pipe bends, elbows, etc. The end result is a system with a simple piping layout which can be factory fabricated.

5. CHALLENGES OF NATURAL CIRCULATION

The first natural circulation based power reactor (63 MWe) Humbholdt Bay 3 in California, USA, came into operation in 1963. The second NC based reactor is Dodewaard reactor in Netherlands which came into operation in 1969 and operated successfully upto 1997. The 50 MWe VK-50 reactor is operational in the Russian Federation since the past 31 years. All these reactors are of the same vintage. Subsequently, no new power reactor was operated with NC as the normal mode of coolant circulation although many concepts like the SBWR have been under active development for several years. In the mean time fossil fuelled power plants have demonstrated the feasibility of operating NCBs up to 660 MWe, several units of which are in operation since 1980. In the recent past several innovative designs are being vigorously pursued the world over. In the backdrop of these activities it is relevant to examine the challenges being faced in the development of NCRs.

Large scale deployment of NC based reactors and safety systems depend on the successful resolution of the challenges specific to natural circulation which are described below.

5.1. Low Driving Force

One of the drawbacks of natural circulation systems is that their driving force is low. The most straightforward way to increase the driving force is to increase the loop height which may be uneconomic. In addition, use of tall risers can make natural circulation systems slender in structure and may raise seismic concerns. Due to these reasons, the incremental height of natural circulation systems compared to the corresponding forced circulation systems is often limited to a few metres (usually less than 10 m).

5.2. Low System Pressure Losses

With low driving force, the only way to obtain reasonably large flow rates is to design for low pressure losses. There are several measures to achieve low system pressure losses:
a) Use of large diameter components/pipes
b) Simplified system and
c) Elimination of components

5.2.1. Use of Large Diameter Components/Pipes

The most straightforward way to reduce pressure losses is to use large diameter components. However, this also results in increased cost and enhanced system volume both of which have economic and safety implications. The large inventory of the passive systems is the direct result of the enhanced system volume. The advantage of large inventory is that it makes all transients sluggish. In case of accidents like LOCA, the large system inventory has a mixed effect. On the one hand it delays core uncovery, but on the other hand it makes available large high enthalpy fluid for discharge into the containment resulting in increased peak containment pressure. Large inventory may also be an unwelcome outcome in case of costly coolants like heavy water.

5.2.2. Simplified System

Generally refers to the simplified piping and equipment layout of the NC system. Minimization of U-bends, elbows, loop seals etc. not only results in simplified system but also results in low pressure losses and prevents phase separation promoting natural circulation flow.

5.2.3. Elimination of Components

An example in this case is the possible elimination of mechanical separators. Elimination of mechanical separators can result in increased carryover and carryunder, both of which are undesirable. While the former directly affects the natural circulation flow, the latter is detrimental to the turbine operation. The alternative to mechanical separators is natural gravity separation. While gravity separation is adopted in several plants with horizontal drums its feasibility is not demonstrated well for vertical reactor vessels. Several studies carried out earlier found it feasible to eliminate the mechanical separators even for this case.

5.3. Low Mass Flux

Low driving force and the consequent use of large diameter components result in low mass flux in NC systems compared to the forced circulation systems. With low mass flux, the allowable maximum channel power is lower leading to a larger core volume compared to a forced circulation system of the same rating. For example, the Russian VK-300, a 250 MWe dual purpose NC based reactor uses the same reactor vessel as that of the 1000 MWe VVER (Kuznetsov et al.) making it almost 3.3 times bigger in volume. In comparison, the 300 MWe Indian AHWR uses almost the same size of calandria vessel as that of the 600 MWe PHWR making it almost twice as big. Large core volumes can result in zonal control problems and stability. Fortunately, these problems are rather well understood now. Size optimisation results in enhanced exit qualities.

5.4. Instability Effects

While instability is common to both forced and natural circulation systems, the latter is inherently less stable than forced circulation systems. This is attributable to the regenerative feedback inherent in the natural circulation phenomenon, where any change in the driving force affects the flow which in turn affects the driving force that may lead to a sustained oscillatory behaviour for certain operating conditions. In addition, due to the low driving force, the stabilizing effect of inlet orificing is limited in NCRs. In forced circulation BWRs, a suitable pump can be selected to achieve stability with inlet orificing without affecting the flow rate. On the other hand, in NCRs, increasing the loss coefficient of the inlet orifice significantly reduces the flow rate which is undesirable.

5.5. Low Pressure Low Flow (LPLF) Regime

In NCRs, the flow rate is a strong function of power and system pressure. Also, in NCRs the flow is stagnant when the reactor power is zero during the initial start up. Further, stage-wise power and pressure raising is relevant to the start up scenarios causing the reactor to operate anywhere between low pressure stagnant (zero power) condition and full pressure nominal flow (full power) condition. In other words, the operating conditions of NCRs can fall in the LPLF regime, where validated thermalhydraulic relationships are not readily available. Specific reactor designs might need an assessment of the applicability of the thermalhydraulic relationships in this regime.

5.6. Specification of a Start-up and Operating Procedure

It is well known that most boiling systems exhibit instabilities at low pressure and low qualities. In many instances instability is observed right from boiling inception which may occur in the tall riser than in the core. Natural circulation reactors are to be started up from stagnant low pressure and low temperature condition. During the pressure and power raising process, passing through an unstable zone shall be avoided as instability can cause premature CHF occurrence. Under the circumstances, it is essential to specify a start-up procedure that avoids the instability. Selection of the pressure at which to initiate boiling and appropriate procedures for pressure and power raising is central to the specification of start-up procedure. In addition, it may become essential to control the inlet subcooling as a function of power. For a cold start-up (first start-up) an external source for pressurization may be required. Due to these reasons the selection of a start-up procedure for a NCR is not always an easy task.

In addition, the procedure for power step back from the normal full power condition also needs to be controlled to avoid landing in the unstable zone. In other words specification of the complete operating procedure is a challenging task for NCBWRs.

5.7. Low CHF

The basis for thermal margin could be the CHF, which depends on the geometric and operating parameters. The main operating parameters of concern are the pressure, flow, exit quality, inlet subcooling and heat flux distribution. There is practically no difference in the operating pressure of NCBWRs and FCBWRs. Since flow in natural circulation reactors is lower, they tend to use the maximum allowable exit quality to minimize their size. In the process, their CHF value tends to be significantly lower than that of FCBWRs. This calls for several measures to increase the CHF.

An acceptable design must satisfy both the thermal and stability margin requirements. For stability there is a lower (Type I instability threshold) and an upper threshold (Type II threshold) between which the system is stable. The lower threshold of instability is generally well below the CHF value and the upper threshold is usually much above the CHF value. The lower threshold is generally avoided by a validated start-up procedure and operational procedure. As a result even in the NCRs, the maximum power is limited by the CHF. Significant power uprating in these designs may require special fuel assembly design features to enhance CHF so as to obtain an optimum sized reactor. The problem is compounded by the fact that some of the parameters like inlet subcooling and strongly bottom peaked axial power profile have opposing effect on CHF and stability.

6. CLASSIFICATION OF NATURAL CIRCULATION SYSTEMS

Natural circulation systems can be classified depending on

1) State of the working fluid,
2) Interaction with the surroundings

3) Shape of the loop,
4) Body force field
5) System inventory
6) Number of heated/cooled channels

6.1. State of the Working Fluid

Depending on the thermodynamic state of the working fluid, NCSs are classified as

a) Single-phase NCSs
b) Two-phase NCSs and
c) Supercritical NCSs

6.1.1. Single-phase NCS

In a single-phase NCS, the circulating fluid in the entire loop continues to remain in only one state. Under this category, liquid or gas filled NCSs are possible. However, liquid filled NCSs are more commonly used for nuclear reactor core cooling. For example, almost all PWRs, PHWRs, VVERs and FBRs are designed to remove the core decay heat by the single-phase NC in the event of Complete Loss of Pumping power (CLOP). Most district heating reactors use single-phase NC as the normal mode of coolant circulation. Typical examples are AST-500 (Samoilov and Kurachenkov (1997)) and NHR-200 (Dazong et al. (1993)). Innovative PWR designs (27 MWe CAREM reactor being designed in Argentina and the 11 MWe ABV PWR being designed in Russia) based on single-phase natural circulation as the normal mode of coolant circulation have also been proposed.

Single-phase gas filled NC systems are used in the cooling of canisters containing radioactive waste in solid storage surveillance facilities. Following a LOCA, it is possible that the HEPA filters of the NPP ventilation system retain the suspended radioactive fission products discharged into the containment. The ventilation systems of NPPs are so designed that NC can remove the heat generated by these fission products in the event of failure of the ventilation fans (Fig. 7). Single-phase NC of air is proposed to cool the containment vessel in AP-1000 and the STAR-LM reactors.

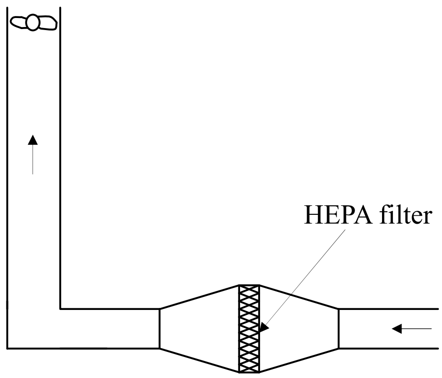


FIG. 7. Schematic of the ventilation system

6.1.2. Two-phase NCS

If a part of the NC system experience two-phase flow conditions, then we refer to it as a two-phase NCS. Two-phase NCSs either with only boiling or with both boiling and condensation are relevant to NPPs. However, gas-liquid NCS (also known as adiabatic NCS) is also possible to be constructed and are used sometimes for experimentation (Hibiki and Ishii (2001)). In certain circumstances, adiabatic NCSs are preferable for phenomenological investigations due to their low operational cost. Adiabatic NCSs (air lift pumps) are also extensively used in reprocessing plants and ADSS.

Generally, two-phase NC occurs in a BWR following the failure of circulating pumps. In PWRs, PHWRs or VVERs it is possible to be observed following the partial loss of coolant inventory in case of a small break LOCA with pump failure. With two-phase systems, it is possible to obtain larger density differences and hence larger flow rates than in single-phase systems. Due to this, many innovative BWRs are being studied with two-phase NC as the normal mode of cooling. Typical examples are AHWR, ESBWR, VK-300, TOSBWR and HSBWR.

6.1.3. Supercritical NC System

These systems operate at or above the thermodynamic critical state. The main interest in supercritical systems stems from the fact that near the critical point there is a large change in the volumetric coefficient of thermal expansion, and hence they are capable of generating driving forces comparable to that of two-phase NCSs. Supercritical systems are more efficient than conventional LWRs. Besides since phase change is avoided separators and dryers can be eliminated along with the problems associated with the occurrence critical heat flux. Another advantage is that the heat transfer characteristics of supercritical water systems are excellent. Because of these, supercritical natural circulation systems are beginning to receive attention from nuclear as well as fossil-fuelled power plant designers. The first fossil fuelled power plant based on NC of supercritical water is operational in UK since 1999 (Franke (2002)). Examples of reactor systems based on supercritical NC are B-500 SKDI (Silin et al. (1993)) and CANDU-X (Dimmick et al. (2002)).

6.2. Interaction with the Surroundings

According to this NC loops can be classified as

a) Closed loop and
b) Open-loop systems

6.2.1. Closed Loop NCS

Close loop NC systems exchange only energy with the surroundings. Fig. 6 is an example of a closed loop NC system. Most nuclear reactor loops relevant to PWRs, PHWRs and VVERs belong to this category.

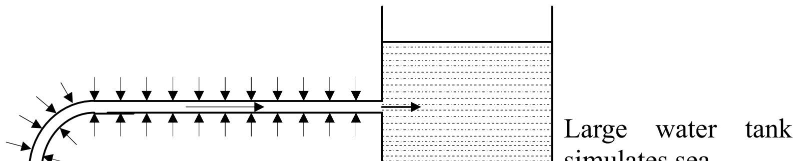


FIG .8. Typical open NCS with a horizontal U-tube for marine applications

6.2.2. Open Loop NCS

Open loop NC systems exchange both mass and energy with the surroundings. Open-loop NCSs are used in ship based reactors (Fig. 8), swimming pool type research reactors, both pressure tube type (Fig. 8) and pressure vessel type BWRs, NCBs, NC based SGs in PWRs, thermosyphon reboilers, waste storage systems, geothermal heat extraction, etc. Most NCSs used in the ventilation (Fig.7) and waste storage surveillance facilities also belong to this category.

6.3. Shape of the Loop

Based on the loop shape, NCSs are classified as toroidal, rectangular, square, figure-of-eight, etc. Such loops are studied mainly for improving our understanding of the natural circulation phenomenon. Toroidal loop (Fig. 10) has been extensively studied because of its simplicity. To the author's knowledge, this is the first loop where multi-dimensional numerical simulations of NC are reported in the literature. Rectangular loops have also been extensively studied for understanding of the steady state, transient and stability characteristics of NC. Stability characteristics of simple rectangular loops have been studied extensively theoretically (Keller (1966), Welander (1967) and Chen (1985)) as well as experimentally (Vijayan et al. (1992) and Misale (1999)). The loops relevant to PWRs and VVERs can be considered to be rectangular for the sake of analysis with different orientation of the heat sink. Figure-of-eight loop is relevant to pressure tube type heavy water reactors (PHWRs).

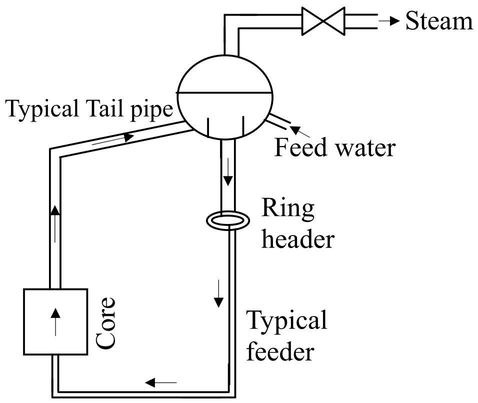


FIG.9. A typical open-loop NCS relevant to a pressure tube type BWR

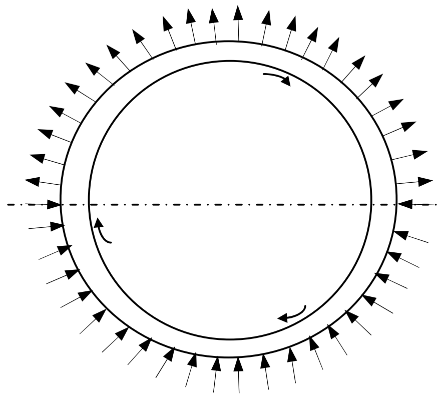


FIG.10.Toroidal loop with bottom half heated and top half cooled

6.4. Body Force Field

Natural circulation systems function only under the influence of a body force field. Two types of body force fields are relevant to NC systems. They are gravity and centrifugal force fields. Most loops in common use work in the gravity force field and are static. However, centrifugal force field can be advantageously employed in cooling of rotating machineries (Davies and Morris (1966)). Such loops are referred to as rotating NCS (Fig. 11) to differentiate it from NCSs operating under the influence of gravity force field, which are stationary. In this case it is possible to have acceleration values several times as big as the gravity acceleration depending on the rotational speed.

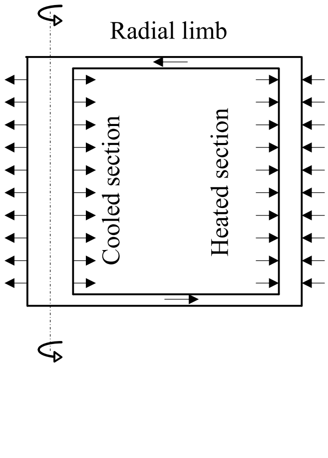


FIG .11. A rotating closed loop

6.5. System Inventory

Depending on the system inventory, one can obtain single-phase NC, two-phase NC or reflux condensation. Single-phase NC is the mode of circulation without inventory loss in nuclear reactors following pumping power failure. Two-phase NC is expected at inventory levels lower than that of single-phase NC. With significant reduction in inventory, the loop circulation breaks down and reflux condensation sets in. In this case, counter current flow in the U-tubes of the steam generator with the steam going up in the centre and condensate falling along tube wall is observed. Even this mode is capable of removing the decay heat although there is no loop circulation.

6.6. Number of heated or cooled channels

Depending on the number of heated or cooled channels, NCSs can be categorized as single channel or multi-channel systems. Multi-channel systems are often referred to as parallel channel systems or loops. Most industrial systems belong to the latter category. Typical examples are power reactor systems like BWR and PWR, NCBs, NC based SGs, etc. However, the average channel behaviour is often studied with single channel. Parallel channel systems can exhibit considerably different steady state and stability behaviour and are often referred to as parallel channel effects.

7. TERMINOLOGIES USED IN NCS

A brief understanding of the common terminologies used in natural circulation will be helpful to the understanding of natural circulation. Typical examples are: hot leg, cold leg, riser, downcomer, recirculation ratio, inlet subcooling, inlet orificing, decay ratio, etc. Some of these terms are described in the appendix-1.

8. CLOSURE

This lecture briefly explains the working principle of natural circulation systems which are mainly employed as heat transport devices in nuclear and other industries. The advantages and the challenges to be overcome for the adoption of natural circulation as the normal mode of coolant circulation in nuclear power reactors are briefly described. Commonly used terminologies in natural circulation systems and the various bases used to classify NCSs are also briefly described.

LIST OF ACRONYMS USED

ADSS	- Accelerator driven subcritical system
AHWR	- advanced heavy water reactor
BWR	- boiling water reactor
CANDU	- Canadian deuterium reactor
CAREM	- NC based PWR being developed in Argentina
CLOP	- complete loss of pumping power
CHF	- critical heat flux
ESBWR	- European simplified boiling water reactor
FBR	- fast breeder reactor
FCBWR	- forced circulation boiling water reactor
GDWP	- gravity driven water pool
HEPA	- high efficiency particulate filter
HSBWR	- Hitachi simplified boiling water reactor
INR	- innovative nuclear reactor
LPLF	- low pressure low flow

LOCA	- loss of coolant accident
LWR	- light water reactor
MWe	- megawatt electric
MWt	- megawatt thermal
NC	- natural circulation
NCB	- natural circulation boiler
NCBWR	- natural circulation boiling water reactor
NCL	- natural circulation loop
NCR	- natural circulation reactor
NCS	- natural circulation system
NPP	- nuclear power plant
PCCS	- Passive containment cooling system
PHWR	- pressurized heavy water reactor
PWR	- pressurized water reactor
TMI	- Three Mile Island
TOSBWR	- Toshiba simplified boiling water reactor
SBWR	- simplified boiling water reactor
SG	- steam generator

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APPENDIX-1: Some common terminologies used in NCSs

Hot leg: Generally used for single phase NCSs and it refers to the pipe from the heat source to the heat sink in the direction of flow, so that it always contains the hot fluid.

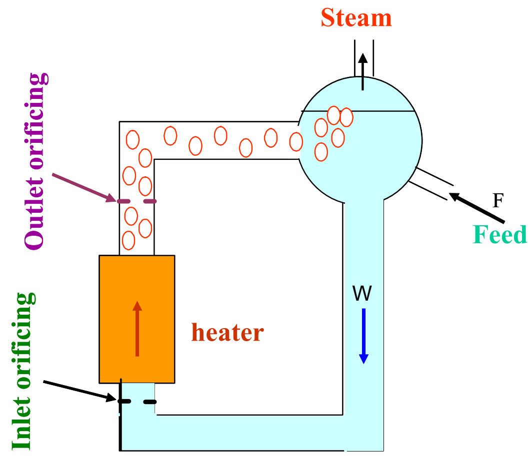
Cold leg: Commonly used in single-phase NC systems to refer to the pipe carrying cold fluid from the heat sink to the heat source.

Riser: This is generally used in two-phase NC systems to refer to the vertical pipe carrying two-phase flow to the separator or the heat sink. Increasing riser height promotes natural circulation flow. An equivalent term used in vessel type BWRs is the chimney.

Downcomer: This is used to represent the pipe carrying the downward flow from the separator or the heat sink to the heat source in case of a two-phase NCS. Usually single-phase flow prevails in the downcomer.

Recirculation ratio: Some times referred to as only circulation ratio and is relevant to an open two-phase natural circulation system such as those relevant to NC based BWRs or steam generators or boilers. This is defined as

$$R = \frac{Loop\ mass\ flow rate}{Mass\ flow rate\ of\ feed} = \frac{W}{F}$$



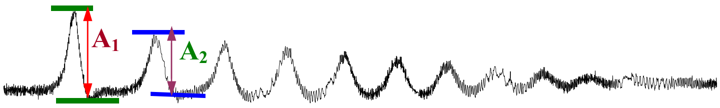
Inlet subcooling: Normally used in the analysis of two-phase systems and is referred to the difference in the saturation temperature and the core inlet temperature. Inlet subcooling is sometimes expressed in terms of enthalpy. In this case, it is the difference between saturation enthalpy and the enthalpy at the core inlet.

Inlet orificing: In two-phase loops, the stability of the system can be enhanced if the single-phase pressure drop is a dominant part of the total system pressure drop. A simple way to achieve this is by incorporating an orifice of the required diameter in the inlet pipe where the flow is in single-phase condition.

Outlet orificing/Exit orificing: This is used sometimes to denote the pressure loss coefficient in the two-phase region, which has different influence on two-phase stability compared to inlet orificing.

Decay ratio, DR: This is defined as the amplitude of the succeeding oscillation to the amplitude of the preceding oscillation, the two oscillations being consecutive. Referring to the figure below, DR can be defined as

$$DR = \frac{A_2}{A_1}$$



In this way, DR<1 indicates a stable system, DR=1 refers to a neutrally stable system and DR>1 refers to an unstable system.