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Technological Perspectives for Propulsion on Nuclear Attack Submarines

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Abstract

This work aims to present the historical context in which the current understanding of the phenomenon of the direct contact condensation started to call the scientific society attention. The development of nuclear power plants Light Water Reactors demanded a safe way to collect and treat the water used to cool the reactor. Some characteristics of this water in a high energetic thermodynamic state made it unsuitable to be directly discharged in the atmosphere. Small room relieves tanks were developed to contain this discharge. These tanks were partially fulfilled with water, and the vapor injection created a vapor plume. In the interface of liquid and vapor, the thermal exchange would be increased by the characteristic turbulence of this region.

Keywords

Direct Contact Condensation, DCC, Relief Tank, Nuclear Power Plants, Vapor Discharge

1. Introduction

After the bombing of Hiroshima and Nagasaki, the world woke in August 6, 1945 for a new era. This fatidic day, which led Japan to surrender, and marked the end of the Second World War, presented a new technology on its darkest side. After war, from the 1950s onward, North American politics sought a new presentation for nuclear power, not related to an uncontrolled nuclear reaction. This new and peaceful path bifurcated in two main roads: naval/maritime propulsion and generation of nuclear energy.

Although controlling a nuclear reaction demanded the development of new technology, overlooked in the rush of the Manhattan Project, Light Water Reactors were soon presented as a safety way to attain the control of a nuclear reaction. The well-known thermodynamically behavior of the water, its good characteristics as a coolant and a moderator, and its chemical compatibility with the uranium dioxide, the most common commercial fuel, made the water a first choice as fluid for the reactor. As a drawback, the water has a high pressure in its vaporization point, which demanded reinforced steel structure in order to retain the high temperature water employed in the cooling circuit of a water reactor.

Boiling pressure vessels were, at that time, standardized in order to withstand the pressure and temperature commons in the use of the industry by codes as the ones produced by ASME B&PV. Safety relief tanks were soon presented as a suitable tool to absorb the discharge of high energetic vapor produced within these boiling pressure vessels, instead of a direct discharge in the environment, which might cause personal injuries and damages. In the particular case of Light Water Reactors, the relief tanks might collect radio activated high energy vapor, condensate it and allow it to be conducted to the radwaste management system. Besides, relief tanks allowed a high velocity discharges to be recollected in small space condensation chambers, what is much recommended to recollect steam in suppression pools of a BWR. These two characteristics are related to the phenomenon of direct contact condensation, which started to figure in the academic literature after 1972. The objectives of this paper is to present the historical context in which took place the development of the technology of relief tanks, linked to the phenomenon of direct contact condensation, related to nuclear generation power plants. For this, newspapers of that time worked as sources for this research.

2. Assumptions and Scope

- It is assumed that the Direct Contact Condensation started to have technical interest as soon as discharge of high energetic vapor from Light Water Reactors needed to be collected and conducted to radwaste management system.
- Direct Contact Condensation is a development that occurred in USA after the II World War.
- The coolant water in a conventional Light Water Reactor may suffer a flash evaporation when suddenly released to radwaste management equipment, and difficult may arise to collect this vapor, as well as damages to the structure of the system.
- Direct Contact Condensation emerged as an efficient way to condense vapor, in a small frame of time and limited space, what motivated this subject to appear in the scientific literature since 1972.
- Direct Contact Condensation is two phase flow, and turbulent heat transfer process. Both of these phenomena help to increment the difficult to obtain a model to describe the injection and condensation process.

3. Development

3.1. Water Coolant Reactors

The design of a relief tank must consider characteristics of the injection as pressure of injection, temperature of injection and temperature of the water in the relief tank, among others. The development of this design emerged as secondary development needed to control a nuclear reaction. Firstly, two uses for a controlled nuclear reaction were proposed: 1) Naval propulsion which started with submarines, and after with surface ships for naval purposes, as aircraft carriers. Civil use of nuclear power in surface ships may be found in icebreakers. Nuclear power for merchant ships was tested, but soon discarded, and 2) electric energy generation.

3.2. Naval Propulsion

The use of nuclear energy for propulsion in naval applications was soon after the II World War proposed. As the words of Admiral C. W. Nimitz, received as a hero in the United States, on the occasion of his return after the capitulation of Japan in World War II, "the possibility of using nuclear energy would extend the U.S. defense frontiers to the whole world" [1].

The submarines, widely used by the Germans in World War II, changed the *modus operandi* of naval warfare by providing an efficient method of denying the use of the sea to the enemy. However, technological development at the end of World War II still imposed serious restrictions on its use. Below the surface, the submarine was slow, and depended on the periscope to determine the position of its target, in such a way that the practice of war required that the submarine operated on surface in order to acquire the position of a target. When the target were acquired, the submarine would submerge and wait the its passage to launch an attack.

In an attempt to overcome these restrictions, the Germans invested in technological innovations such as 1) snorkel, which allowed air to enter within the submarine. This way the submarine, still submerged would be able to turn its Diesel-Generator to feed its batteries, 2) submarines with increased battery capacity, which allowed an autonomy of 30 nautical miles at 15 knots, or 285 nautical miles at 6 knots, and 3) a system operated by a closed oxygen cycle, which would be released by chemical processes [2].

It was clear to the US government that increasing submarine autonomy and speed was a matter of military and economic importance, hence the postwar US Navy, whose Chief of Naval Operations was C. W. Nimitz, understood that the solution for these technological restrictions on the use of submarines could lie in the use of nuclear energy.

However, it was necessary to develop a reasonably efficient way of transforming the thermal energy generated in the core of a reactor in mechanical shaft energy. The current technology so developed allowed only the construction of gas-cooled experimental reactors (Chicago Pile # 1 and # 2), and large-scale, graphite-moderated/water-cooled reactors: B-Reactors, built In the Hanford site [3]. These latter were commissioned for the production of plutonium, which would equip Fat Man, the bomb that was launched in Nagasaki. Therefore, the option of using a water as a cooling fluid in a nuclear reactor had a historical antecedent. In a concurrent design, sodium had also some attractive points: thermodynamic characteristics such as high thermal conductivity, high specific heat and high vaporization temperature (883˚C). This latter characteristic allowed the cooling circuit of a reactor to operate at pressures close to the environment, reducing its structural requirements.

Admiral H. G. Rickover decided to develop both reactor concepts simultaneously, resulting in two different reactors: S1W, PWR reactor to equip the USS Nautilus (SSN-571) by Westinghouse and commissioned in 1954; and S2G, a Metal Liquid Reactor to equip the USS Seawolf (SSN-575) by General Electrics and commissioned in 1957. In both contracts, it was planned to construct a prototype to be installed on land, an operational reactor to be installed in the submarine, and a spare reactor [4].

Although the USS Seawolf have completed her sea trials, some major drawbacks in the sodium cooled project made it less attractive than the water cooled project, and the sodium-cooled reactor was deemed by Admiral Hickover as expensive, complex, and difficult to repair. (1). Sodium has a melting point of almost 100˚C and demands permanent heating, otherwise, it will solidify. This fact imposes difficulties to the maintenance: once the reactor is shut down, the sodium coolant must be kept warm. Also, sodium presents large thermal expansion. This facts increases the fatigue stress over the refrigeration loop. Sodium has no chemical compatibility with water, and produces a long half-life isotope when activated, what demands heavy loads of lead to shield the loop.

At this point in history, 1953, US President D. Eisenhower, gave the “Atoms for Peace” speech to the United Nations Assembly, in which proposed ways of civilian and peaceful use of nuclear energy as an alternative to curb the arms race [5]. In essence, this speech proposed the creation of an international agency (IAEA) responsible for overseeing the peaceful use of nuclear energy through the imposition of safeguards, and for assisting its members in developing technological applications of nuclear energy for peaceful purposes. “The proposed international atoms-for-peace agency will have an elaborate system of safeguards to make sure its nuclear resources are not diverted to military uses” [7].

A direct consequence of this philosophy in the application of nuclear energy was the approval of the Atomic Energy Act in 1954. This law established the favorable conditions for the exploitation of the use of nuclear energy by private companies. Thus, electric power generation presented itself as an excellent option to show the world the non-destructive potential of this new form of energy.

In this historical context, it was the responsibility of the American Navy, which led the development of both energy and water-cooled reactors, to supervise the development of a plant for this purpose.

At the time, the American Navy predicted technical setbacks in the use of sodium. Sodium is not a moderator element in such a way that it becomes essential to use in conjunction with a low atomic number element. Still, S2G was a reactor whose neutron energy was intermediate, a fact that made the reactor require a larger load of uranium-235 because of the reduced uranium shock section for this energy range. Sodium is also chemically reactive, causing an exothermic reaction and release of hydrogen when exposed to water. Furthermore, sodium is subject to the reaction generating the Na-24 isotope, whose half-life of about 15 hours required and increase in weight to the submarine, which would have to have the shielding of its reactor cooling circuit increased [2].

3.3. Generation of Energy

The fact that the production of PWR reactor was, at that moment, in a later stage than the production of the Metal Liquid Reactor, made Rickover decide to order the first nuclear reactor for the energy production, using water as coolant.

This fact was decisive for the establishment of a Standard in the US nuclear industry, both related to power generation and naval propulsion. Under this orientation, in 1957, Shipping Port Power Station, the first PWR-type nuclear power plant exclusively dedicated to electric power generation [6], was commissioned. Producing 72 MW of energy, the project of this reactor was implemented as a partnership between the DOE, responsible for the Reactor, Reactor Cooling Circuit, and Steam Generator; And the Duquesne Light Company, responsible for the section of the plant directly related to the generation of electric power [8].

Still following these premises, United States government sought to conciliate a peaceful coexistence with the nations that were allied to them. Demonstrating a peaceful way of using nuclear energy, the construction of a nuclear merchant ship (cargo/passengers) was proposed. The objective would be to present to the various countries a peaceful application of nuclear energy [9]. This ship, NS Savannah, was commissioned in 1962. Notwithstanding the operational success of this ship, maintenance costs were critical to the end of its active life in 1971, so that this application did not achieve economic importance.

Even so, the venture has succeeded in spreading the peaceful use of nuclear power [10]. Nevertheless, having been effectively put into practice, the peaceful essence of the program was followed by the period of nuclear tension that characterized the Cold War period.

"Atoms for Peace" program focused on the design, development and implementation of nuclear power generation plants. Under this *aegis*, some 286 research reactors were commissioned at this time [11], among them the IEA-R1 in Brazil, designed by the US company Babcock & Wilcox, and located at the Nuclear and Energy and Nuclear Research Institute, In São Paulo-SP [12]. This reactor reached its first criticality in 1957, having been inaugurated by President Juscelino Kubitschek in 1958.

3.4. Development of Pressurizer Technology

In the previous subsection, the causes that led the US government to choose the PWR reactor design were exposed. In this subsection, technological innovation that this type of technology demanded will be commented.

The concept of PWR reactors was partly inspired by the design of common boilers, where the heat of combustion is channeled through heat exchanger tubes that are part of a Steam Generator, responsible for producing the necessary steam to drive a turbine, responsible for the transformation of the thermodynamic energy of the circuit in shaft power.

The proposal of a PWR reactor, in a simplified way, is to change the heat source of a common boiler by a nuclear reactor cooled by water. In this way the water responsible for removing core heat plays the role formerly played by combustion gases. To do so, it must be brought to a temperature high enough to achieve a reasonable level of thermodynamic efficiency to force the vaporization of the water on the cold side of the heat exchanger. This is the technical challenge, since no industrial application had used so high temperature water until then, which would require a high pressure, in order to avoid vaporization. Although the US Navy's Bureau of Engineering in the 1930s suggested naval use of high-pressure steam applications [2], the development of nuclear standards for the application in pressure vessels, pipes, structures, specific valves for steam within high energy, demanded new standards, which were materialized by ASME BP&VC Section III—Rules for the Construction of Nuclear Facility Components, and occurred only in 1963.

The structural design of a Pressurized Water Reactor provides primary structures with structural reinforcement to ensure resistance to high pressures, which are necessary to withstand the liquid state of the water, under high temperatures. Thus, it is expected to operate all equipment and fluid circulation in the primary piping of a PWR plant with water in liquid state, except for the Pressurizer, where biphasic refrigerant operation is expected. The pressurizer is the equipment responsible for controlling the pressure of the reactor cooling circuit.

The pressurizer consists of a pressurized vessel connected at its bottom to the Reactor Cooling Circuit, with an atmosphere partially filled by some inert gas. This gas allows small changes of volume in the primary loop to be compensated. N_2 may be chosen in order to create a chemically inert atmosphere in the presence of H_2 originated. This pressurizer is partially filled by steam, originated from the high energetic conditions in which the water in the liquid state of the cooling circuit of the reactor is. The pressurizer is responsible for: 1) pressurize the Cooling Circuit of the Reactor at the beginning of operation of the plant; 2) maintain constant pressure in the Cooling Circuit of the Reactor during the operation of the plant in permanent regime; 3) limit the rate of change of pressure during reactor operating transients; and, 4) impose a maximum limiting pressure value on the Reactor Cooling Circuit. Safety devices, e.g., Safety Relief Valves are designed to open once the threshold pressure is exceeded. When there is a variation of the power produced by the reactor, or the power removed from the Cooling Circuit of the Reactor by the Steam Generator, a corresponding temperature variation of the cooling fluid occurs. Temperature increase correspond to the decrease in density and increase in total volume of the space occupied by the cooling fluid, further confining the gas atmosphere present in the pressurizer dome, producing a final increase in the pressure. Analogously, the reduction in temperature causes a drop in pressure. The primary circuit pressure of a PWR may be controlled by the direct operation of resistance banks located at the bottom of the Pressurizer in order to raise the temperature of the water causing an increase in pressure or by sprinkling of cooled water in the Atmosphere of the pressurizer in order to reduce the vapor pressure. The cooled water to be sprayed is removed from the cold leg of the Cooling Circuit of the Reactor. In extreme cases of high pressure, the pressurizer has a Safety Relief Valve that opens and discharges steam into a relief tank [13], so that the maximum pressure is limited to 10% or 20 Kpa above the design pressure.

The Pressurizer Discharge System consists of the relief tank, a relief valve, an expansion valve, piping to conduct the steam from the Pressurizer to the Relief Tank, and the Relief Tank itself. The Relief Tank does not constitute a component related to the safe shutdown of the reactor, prevention and mitigation of accidents and is therefore classified as an equipment that does not exercise safety function. It belongs to the "D" Quality Group [14]. For this, it can be designed observing the standard ASME Boiler and Pressure Vessel Code, Section VIII, Division 1 [15]. Although it is not an equipment with nuclear safety classification, the Relief Tank must meet the GDC in its item 2, which establishes that the failure of items not related to safety due to seismic activity may not cause adverse effects to the operation of equipment that they carry out Safety function. Because of its proximity to the Primary Cooling Circuit, the Relief Tank is located within the containment, near the reactor vessel. The GDC 2 service can be performed in two different ways: By arrangement criteria, it can be predicted that the tank failure due to seismic activity occurs at a safe distance, or that there are physical barriers that prevent adverse effects on items performing safety functions.

In order to meet the criteria established in GDC 2, it is sufficient to observe the prescription of Regulatory Guide 1.29 [16]. Furthermore, the Relief Tank, at the time of pressure relief, must guarantee sufficient structural strength to not generate missiles, according to GDC in its item 4. Otherwise, all systems that perform a safety function in the vicinity of the Tank would have to be protected from the Relief Tank, so that they would not be subject to missiles generated by structural failure. These are the basic design criteria for the Relief Tank, as provided in the US Nuclear Regulatory Commission (SRP). Because the Relief Tank is located near the Reactor Cooling Circuit, it becomes impracticable to move it away to meet the GDC 4. Otherwise, the structural reinforcement of this tank is the solution chosen in order to prevent its collapse, instead of applying missile protection to systems that perform safety-security functions.

The purpose of the Relief Tank is to provide the ideal conditions for the rapid condensation of the injected vapor, through the phenomenon of direct contact condensation. The phenomenon of condensation by direct contact consists of the injection of substance in a vaporous state in a liquid medium, in order to effect thermal exchange leading the vaporous substance to the change to liquid phase. This process is characterized by high thermal efficiency, due basically to two factors: 1) the thermal exchange between the vaporized substance and the liquid medium takes advantage of the formation of a turbulent interface layer. The turbulence increases microscopically the convective thermal flow between the adjacent layers of flow. The latent heat of vapor condensation is responsible for absorption of large amounts of heat from the vaporous medium.

An important application for the nuclear area is to enable the containment of the vapor discharge at high temperature and pressure, originated from the pressurizer, located in the primary circuit of nuclear plant, thus avoiding the emission of fission products, radioactive corrosion and tritium to the environment, without first undergoing treatment. By this method, the vapor can be contained in a relatively small tank.

After being released by the Safety Relief Valve, the wet vapor contained in the Pressurizer undergoes an adiabatic expansion becoming dry vapor, and is potentially contaminated by tritium, activated corrosion products, and fission products, depending on the direct contact with the rods of the fuel elements. Such contaminants prevent the fluid from being directly discarded in the environment, without first undergoing physic and chemical and radiological control that guarantees the fulfillment of criteria for disposal.

To maximize the condensation rate of this vapor, this mass is injected under an undercooled water bath contained in the Relief Tank. The subcooling temperature is the difference between the saturation temperature and the bath water temperature. Injection under these conditions can produce a shock wave in the neck of the injector nozzle. The injection dynamics for subsonic jets is quite different from the injection dynamics for supersonic jets, such that the mean heat transfer coefficient of subsonic jets is about 1/5 to 1/10 of the value found for sonic jets [17]. Relief tanks, therefore, are devices designed to contain and execute rapid condensation of a jet of steam, often injected at sonic speed, under high pressure and temperature.

In order to ensure compliance with the criteria established in GDC item 4 (protection of systems that perform missile safety functions) and to allow a reduction in the volume and/or structural capacity of the Relief Tank, it is sought to determine the injection parameters Which influence the dynamic and static charge generated by the steam injection, which is supported by the tank. Among the parameters of importance for the design of the relief tank design are the dimensions and shape of the plume, the coefficient of heat exchange between steam and water, and the definition of a condensation map.

4. Conclusions

As above exposed, the technology of injection of high energy vapor in water was developed as an application to be used in nuclear facilities as an efficient way to contain contaminated water within instead of having it released to the atmosphere.

The direct contact condensation is a thermodynamic phenomenon which allows the fast condensation of the vapor in a small space. However, the correct understanding of this process is demanded, once mistakes made when dimensioning the relief tank may compromise the accomplishment of GDC 4, since the blow out of this relief tank would create missiles. In this case, for its proximity with safety related systems, safety functions would be compromised. Also, the relief tank must comply with GDC 2, and not cause the failure of a safety related systems, in the case of seismic activity.

Currently, the injection phenomenon is reasonably well understood, however analytical and numerical procedures still present some degree of fail to model regions where turbulence and two-phase flow.

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