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Design and Selection of Innovative Primary Circulation Pumps for GEN-IV Lead Fast Reactors

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Abstract: Although Lead-cooled Fast Reactor (LFR) is not a new concept, it continues to be an example of innovation in the nuclear field. Recently, there has been strong interest in liquid lead (Pb) or liquid lead–bismuth eutectic (LBE) both critical and subcritical systems in a relevant number of Countries, including studies performed in the frame of GENERATION-IV initiative. In this paper, the theoretical and computational findings for three different designs of Primary Circulation Pump (PCP) evolving liquid lead (namely the jet pump, the Archimedean pump and the blade pump) are presented with reference to the ALFRED (Advanced Lead Fast Reactor European Demonstrator) design. The pumps are first analyzed from the theoretical point of view and then modeled with a 3D CFD code. Required design performance of the pumps are approximatively around an effective head of 2 bar with a mass flow rate of 5000 kg/s. Taking into account the geometrical constraints of the reactor and the fluid dynamics characteristics of the molten lead, the maximum design velocity for molten lead fluid flow of 2 m/s may be exceeded giving rise to unacceptable erosion phenomena of the blade or rotating component of the primary pumping system. For this reason a deep investigation of non-conventional axial pumps has been performed. The results presented shows that the design of the jet pump looks like beyond the current technological feasibility while, once the mechanical challenges of the Archimedean (screw) pump and the fluid-dynamic issues of the blade pump will be addressed, both could represent viable solutions as PCP for ALFRED. Particularly, the blade pump shows the best performance in terms of pressure head generated in normal operation conditions as well as pressure drop in locked rotor conditions. Further optimizations (mainly for what the geometrical configuration is concerned) are still necessary.

Keywords: nuclear energy; LFR; Generation-IV; pumps; CFD; liquid metal; ALFRED

1. Introduction

Although Lead-cooled Fast Reactor (LFR) is not a new concept, it continues to be an example of innovation in the nuclear field. Starting from the initial researches related to its use for naval (submarine) propulsion dating to the 1950s, Russian researchers pioneered the development of Heavy Liquid Metals (HLM) reactors. More recently, there has been increasing interest in liquid lead (Pb) or liquid Lead–Bismuth Eutectic (LBE) both critical and subcritical systems in a relevant number of

Countries (e.g., [1–4]). The increasing knowledge of the thermal-fluid-dynamic properties of these heavy fluids and the selection of the LFR as one of the six system types chosen by Generation IV International Forum (GIF) [5] for further R&D fostered the exploitation of new solutions and concepts to optimize the key components to be adopted in the 300 MW_{th} pool-type Advanced Lead Fast Reactor European Demonstrator (ALFRED) aimed at proving the feasibility of the conceptual solutions selected for the European Lead-cooled Fast Reactor (ELFR).

In this paper, starting from a previous preliminary work [6], we present theoretical and numerical results for three different designs for the Primary Circulation Pump (PCP) involving liquid lead for the considered ALFRED design (namely a jet pump, an Archimedean pump and a blade pump) and a preliminary comparative selection of the most suitable design.

The pumps are at first analyzed at design operating conditions to optimize the geometry on the basis of to the velocity triangles and then they are modeled by proper CFD simulations. The pumps are analyzed at different flow regimes to find the optimal design point maximizing the mass flow rate at operating conditions and minimizing the pressure losses at Natural Circulation (NC) conditions. This choice is due to the requirement of having a detailed 3D simulations that take into account both the specific geometry of each pump and the boundary and turbulence effects of the flow. Moreover, the use of molten lead has a relevant impact on the thermal-fluid-dynamic pump design due to the key requirements necessary to avoid erosion and stagnation effects. These requirements, along with the design specifications, dictate the geometry, reliability and performance of the pump.

2. Background

2.1. Lead as Liquid Metal Coolant for Fast Reactor

Liquid metals are used as coolant for fast reactors (FRs), where neutrons generated during the fissions chain are not moderated. Lead and its alloys have been proposed as cooling media; LBE was chosen as the coolant for some submarine reactors (Alpha class) in the former Soviet Union; more recently there has been renewed interest in lead and LBE coolants for civilian FRs. In these nuclear power plants (NPPs), fast neutrons support the chain reaction because, looking at the lead cross sections, it is very small for absorption and high for scattering (also thanks to its high atomic number): the final discharge fuel burnup is high since the so called "closed cycle" [7] can be implemented, thus substantially reducing the accumulation of highly radioactive waste.

Concerning safety features, lead has high boiling point, very low vapor pressure and high γ shielding capacity; additionally it retains fission products (e.g., Cs and I) released from the core in case of cladding failure and it does not react violently with water and air. Moreover, lead has high thermal capacity and heat transfer coefficients: the very low likelihood of damage to the core is enforced by the above cited characteristics. In the following Table 1, a comparison is shown between the main thermo-physical proprieties of water (at typical operating pressure of a pressurized water reactor), sodium and lead.

Table 1. Thermo-physical proprieties of water, sodium and lead: above the name of the coolant were reported the normal operating conditions in the nuclear coolant system use [8].

Coolant / Proprieties	H_2O (155 bar, 573 K)	Na (1 bar, 673 K)	Pb (1 bar, 673 K)
Density (kg/m^3)	727	856	10563
$T_{melting}$ (K)	-	371	601
$T_{boiling}$ (K)	618	1156	2023
Heat capacity (J/(m^3·K))	3.9×10^6	1.1×10^6	1.5×10^6
Dynamic viscosity (Pa·s)	0.09×10^{-3}	0.28×10^{-3}	2.23×10^{-3}
Thermal Conductivity (W/mK)	0.6	72	17
Vapor pressure (Pa)	8.6×10^6	52	2.8×10^{-5}

Lead shows some advantages compared with water and sodium. It has a significantly higher boiling point with two main consequences:

- LFR can, in principle, operate at higher temperature than SFR, increasing thermal efficiency and ensuring a substantially higher safety margin
- Primary system pressurization is not necessary, as it must be done in the case of water; safety of the system is improved as the probability of loss of coolant accident is practically eliminated.

Furthermore, lead does not react with water or air, at variance of sodium which spontaneously ignites in air and reacts explosively with water; sodium therefore requires an intermediate coolant loop (usually implemented via a primary and a secondary loops) with higher costs and lower thermal efficiency.

Looking at sustainability, lead is available in relevant quantities also in a scenario with a high number of reactors in use.

Despite all these advantages, lead as coolant for a fast reactor has also some disadvantages and problems still unresolved. Lead is more corrosive to steel than sodium. Moreover, the melting temperature of sodium is 97.72 °C, lower than lead's temperature, and this could bring more difficulties in the case of solidification of the coolant if unlikely reactor should operate at low temperature.

Hence, the properties that make lead suitable for being used as coolant in fast reactors are:

- It does not react with air and water, therefore the intermediate loop can be removed, and the steam generators can be installed directly within the Reactor Vessel (RV). In case of coolant losses, the requirements will be less stringent
- Very high boiling point, hence the presence of voids or core uncover are reduced
- Density greater than the fuel, therefore, a core catcher is not required to deal with a core melting accident: there is no risk of return to criticality after meltdown
- Low absorption cross section and low moderating power, therefore a very compact fuel assembly is not necessary, then the passage section in the fuel assembly is large enough to maintain a low speed, low pressure drop, reduce pumping power and to obtain a large capacity to sustain NC.

The use of lead (or similar lead alloys) as the coolant in advanced FRs needs of high-temperature operation and requires structural materials qualified for these reactors. Known structural alloys like the ferritic-martensitic T91 and the austenitic stainless steel 316L have been an initial choice, but they have the problem to undergo severe dissolution attacks.

As known, corrosion is one phenomenon to be investigated for the qualification of a structural material. Other important phenomena are erosion, material failure under static loading (e.g., brittle fracture) and failure under time-dependent loading (e.g., fatigue and creep); this is the most important effect that limit the velocity at the tip of the blade in the axial pump configuration, with the consequent choice of a very low rotational speed with respect to the conventional industrial application.

2.2. *ALFRED (Advanced Lead Fast Reactor European Demonstrator)*

As part of the 7th Framework Program Lead-cooled European Advanced Demonstration Reactor (LEADER) project, the conceptual design of a lead-cooled fast demonstrator reactor, ALFRED has been carried out. The conceptual configuration of ALFRED is shown in Figure 1 [6]; its aim is to develop a fully representative, scaled demonstrator of the industrial European Lead Fast Reactor (ELFR, also defined in the LEADER project), representing a guideline for its design and construction in terms of costs, safety, components and technologies. The ALFRED key parameters are reported in Table 2 [6].

Because of the requirements of inspection and removability for all the main reactor components, all of them are specifically designed to be removable (independently and separately) from the reactor.

The design of the (mechanical) PCPs is such that they are enclosed in hot manifolds allowing for their removal from inside the inner vessel and contributing to the compactness of the plant. Different configurations for the key components of ALFRED are under evaluation, including a new design and arrangement of the steam generators, of the auxiliary equipment and of the PCPs, in order to find the optimum both at the single component and at the whole reactor. Concerning the PCP development, various configurations are presently under evaluation: particularly, this paper presents the computational evaluation of three different designs, focusing on the most promising one.

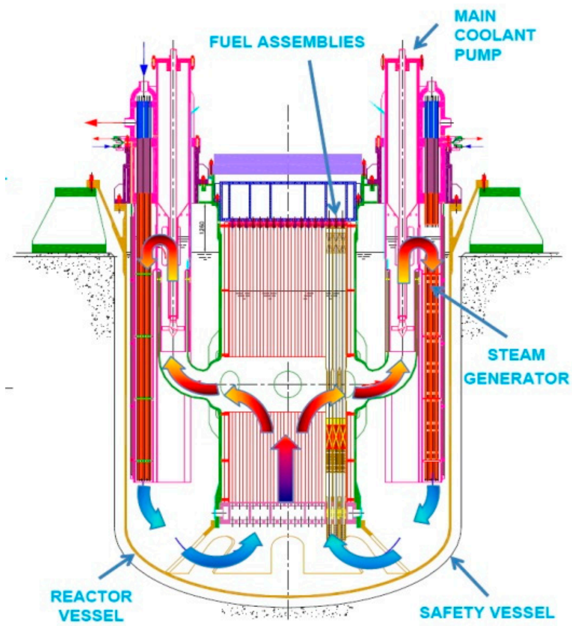


Figure 1. Conceptual configuration of ALFRED.

Table 2. ALFRED key parameters [6].

Parameter	Value
Power	300 MW_{th}
Primary coolant	Lead
Primary system	Pool type, compact
Primary side lead temperature	400 ÷ 480 °C
Primary coolant circulation (at power)	Forced (mechanical pumps)
Primary pump	8, mechanical, removable, located in hot leg inside the inner vessel
Steam generator	8, once-through, removable, integrated in the main vessel
Secondary cycle	Water superheated steam at 180 bar, 335 ÷ 450 °C
Decay heat removal	2, independent, redundant and diverse DHR systems
Overall efficiency	40% (or higher)
Internals	All internals removable

Two possible architectural solutions are proposed in this work for the pump installation: pull-type or push-type primary pump. In the first configuration, the suction side of the pump is placed at the top and the discharge side at the bottom, vice versa for the 'pull' type (see Figure 2).

3. Results

Generally, a pressure based incompressible calculation has been performed, with isothermal and turbulent flow modeling. For this purpose, no investigations were performed in terms of temperature influence, because the maximum velocity and the pressure drop when the pump is off are the limiting constraints: the influence of different operating temperatures is very small so that in the model adopted all the wall boundaries conditions are settled as adiabatic, and the lead properties are imposed constant and calculated at the core outlet fluid flow mean temperature, equal to 480 °C.

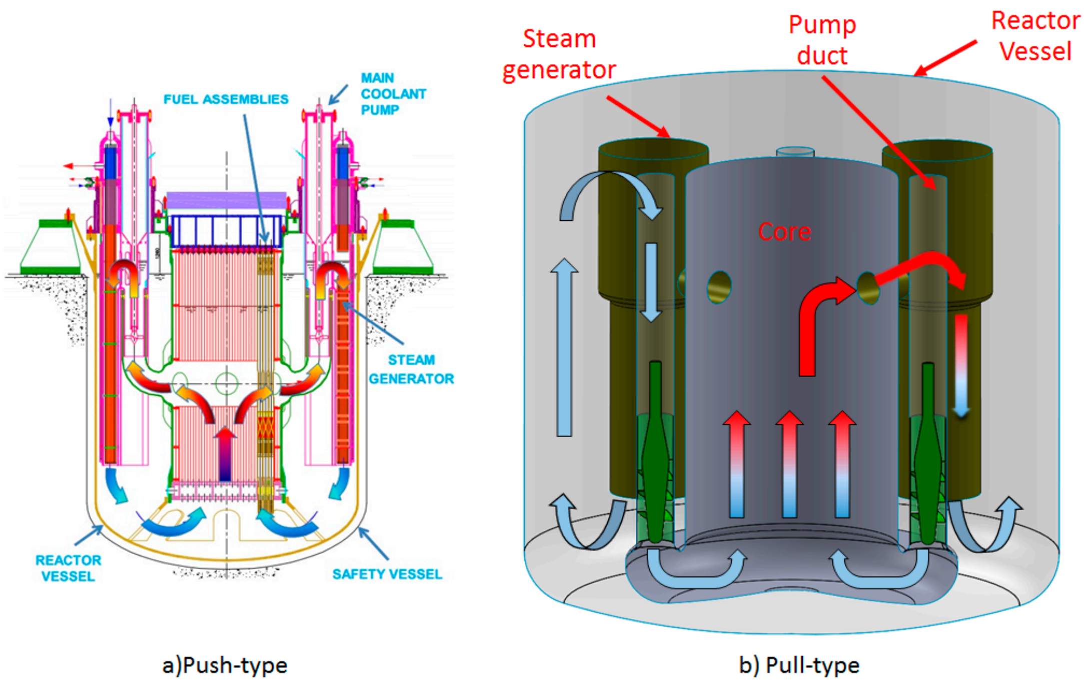


Figure 2. (**a**) push-type configuration; (**b**) pull-type pump configuration.

The equations suggested for the calculations of the molten lead properties are reported in [8] and in particular, in Table 3 has been reported those for density and dynamic viscosity.

Table 3. Liquid lead properties equations [8], T is the Temperature expressed in K.

Density (kg/m^3)	$\rho = 11441 - 1.2795 \times T$
Dynamic viscosity (Pa·s)	$\mu = 4.55 \times 10^{-4} \times e^{(1069/T)}$

Regarding the turbulence model, the k-ω SST [9] was adopted for all the calculations performed. The selected model allows the creations of different structure of mesh at the wall, with a different resolution of the near-wall flow nodes equations depending on the y^+ values, that shows in which of the sublayer (viscous, buffer or log-law layer) the nodes are placed (see [10,11] for more details). Considering the non-implementations of ad-hoc wall functions for liquid metals in ANSYS FLUENT® 17.0, and preferring the near wall flow resolutions requiring a y^+ value of less than 1, the grid and the mesh size increase the computational expense of the calculation. Working with liquid lead, the computational grid was therefore created with a very fine mesh at the blade and recirculating/critically zones, while in the straight part of the domain a larger size of the cells (normal to the wall surface) was selected, in order to limit the computational weight of the mesh (around 32 Gb of RAM).

The entrainment of cover gas in the flow is a possible issue of all systems designs characterized by the existence of free levels. This can be taken into account and evaluated by specific CFD calculations using a multiphase approach (e.g., VOF), as already used in the steam generator design calculation reported in [12]. Such phenomena are strongly dependent on the specific location of the pump in the primary system and have not been directly addressed in this work being the object of a separate research branch.

The optimal performances search for each geometry investigated has been conducted with two general goals:

(a) The minimization of maximum velocity on the blade or in the neck section: at the driver tip for jet pump and on the peripheral sections or at the tip of the blade in the crew and semi-axial configurations
(b) The minimization of the pressure loss at pump off in locked rotor conditions: this is considered a very important requirement to allow the establishment of the natural circulation; for some configurations (like the jet pump) the issue is solved at design level but, for the screw and the blade pump, a particular design of the blade and an accurate sizing of the inlet and outlet section is required to minimize pressure losses in natural circulation.

Obviously, for each pump further optimizations are developed, in terms of efficiency or to avoid recirculating zones in particular sections, although the primary design requirements are based on the previously exposed mass flow rate and required head in conjunction with the structural and safety consideration based on velocity and pressure losses. In the following, through investigations of these aspects are presented.

3.1. Theoretical and CFD Simulation of the Jet Pump

The reasons behind the detailed analysis of the jet pump are related with the safety requirements of a GEN-IV reactor PCP: to enable the coolant NC also in accidental scenarios, to guarantee the heat removal from the core even in the case of failure of any (Design Basis Scenario) or all (Station Black-out Scenario) of the 8 PCPs. The jet pump geometry is particularly suitable for enabling the NC since there are no moving parts and obstacles (such as blades or screws) inside the pump that could hinder the fluid flow.

This paragraph presents a computational model of a jet pump evolving liquid lead as PCP for a GEN-IV LFR nuclear power plant adopting the ALFRED operational conditions, by assessing its behavior at various mass-flow rates and different geometries, and optimizing its performance through an in-depth 3D CFD analysis based on the established package ANSYS Fluent [13]. To complement the 3D CFD analysis in the design and optimization phases, the 1D Jet Mixer feature a system code has been used [14]. In [15] an in-depth analysis of the jet pump evolving molten lead for ALFRED is presented.

The necessity to provide a driver flow and the requirement to extract the pump from the reactor enforces a re-design of the whole reactor with respect to the conceptual design reported in Figure 1. The geometrical layout of the reactor for the jet pump envisions a driver flow flowing downward, the suction-side flow entering the jet pump close to the free surface and the jet pump discharging in a pressure chamber immediately below the core. The geometrical layout and a comparison with the conceptual design are reported in Figure 3.

Because of the unavailability of an extensive set of experimental data for jet pumps evolving liquid lead as working fluid, as a first approach a jet pump evolving water as working fluid has been modeled according to a classical theoretical model [16] to validate the simulation model by comparing the theoretical predictions with a set of experimental data for a water jet pump [17], get more sensibility about the jet pump behavior, and analyze how the operational parameters affect its features. The results of the theoretical model for the jet pump evolving water matched excellently the experimental data with an averaged error less than the 5%, as reported in [6], validating the approach and the modeling technique. Furthermore, a set of simulation that investigate a Venturi nozzle (very similar to the Jet pump) evolving liquid lead, and clearly shown a very good agreement between CFD and experimental results is reported in literature [18], with an averaged error greater than the simulations with water but which does not exceed the 8% in the steady calculations.

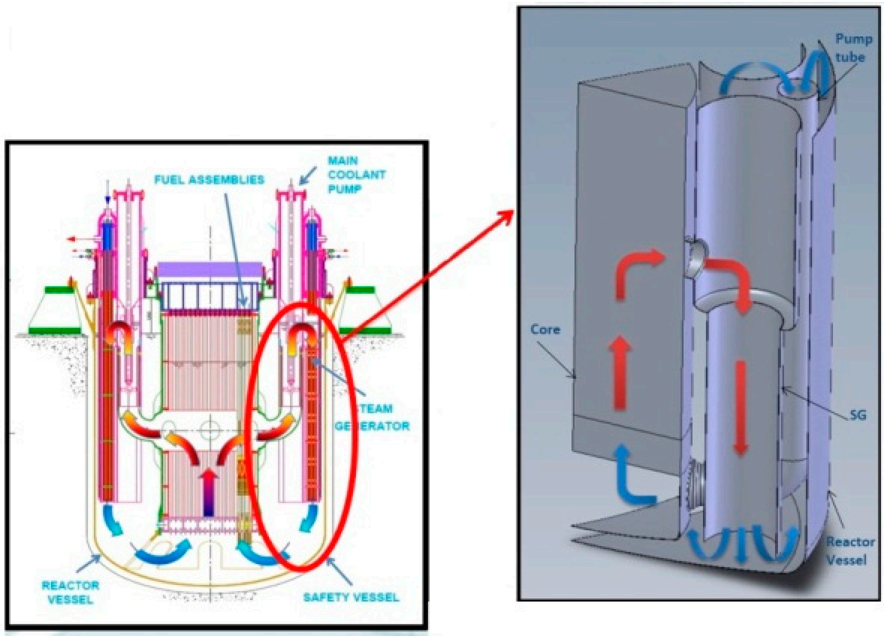


Figure 3. Comparison between the conceptual (**Left**) and the jet pump-based configuration of ALFRED (**Right**).

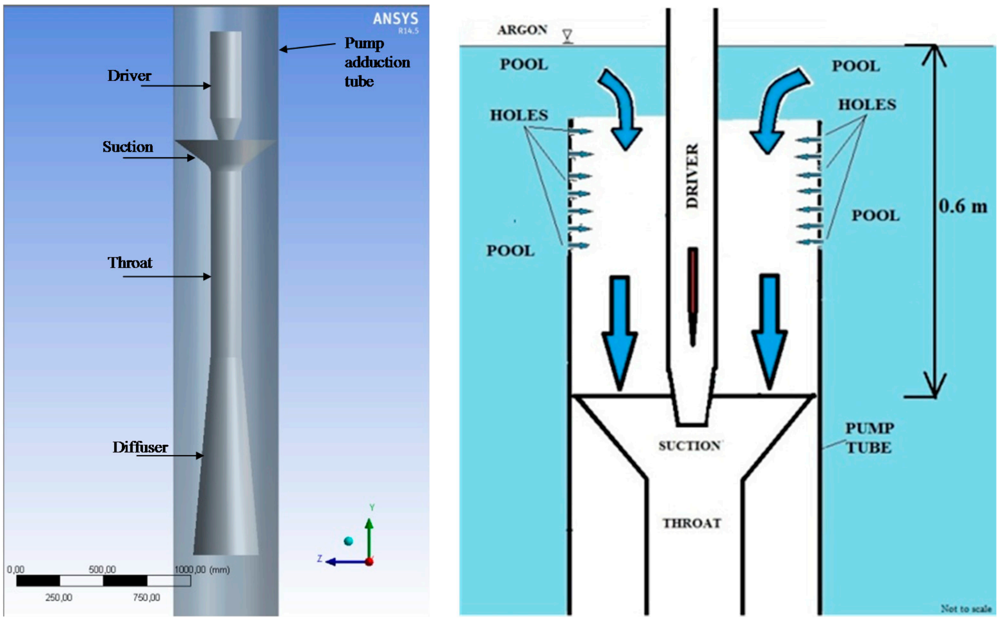
The jet pump evolving liquid lead as working fluid and designed to be located in ALFRED has the following constraints:

- The pump is placed inside the pump tube, which has a diameter of 0.6 m and a longitudinal length of 8 m
- The pump operates with lead entering the tube at 400 °C from the top, near the free surface of the pool, and/or from holes in the upper part of the tube
- The pressure at inlet and outlet are affected by the hydrostatic head
- The pump must ensure a head of at least 1.5 bar to provide the required coolant circulation and compensate the pressure losses in the circuit
- The volumetric mass flow rate must be 0.31 m^3/s (3274 kg/s) at each pump
- Proper provisions shall be applied to minimize the pressure loss at NC conditions.

Using the hydrodynamic similarity and imposing the thermo-mechanical properties for lead [8] in the theoretical correlations [16], a first-guess geometry for the lead jet pump (Figure 4a) and for the flow patterns (Figure 4b) have been obtained.

The viscous, isothermal and adiabatic features have been selected for the physical model, using the k-ε model for turbulence and the Standard Wall Function as Near Wall Treatment. Concerning the Near Wall Treatment, the range 30 ÷ 300 has been selected for y^+, as suggested in literature [15]. Furthermore, steady state condition has been simulated. The Boundary Condition of Pressure Inlet has been set for the inlet suction zone, the Boundary Condition of Pressure Outlet has been set for the outlet diffuser zone and a Boundary Condition of Inlet Mass flow rate has been set for the driver zone. Two criteria have been chosen to assess the quality of the simulation:

- The inlet mass flow rate at suction: this parameter has been evaluated until it remains constant
- The convergence of the residuals, evaluating the residuals trend during the simulation: it is considered acceptable a convergence of at least 1.0×10^{-5}.



(**a**) (**b**)

Figure 4. Lead jet pump: (**a**) geometry model; (**b**) flow patterns.

Starting from the first-guess configuration, a parametric CFD study has been carried out varying the geometrical and physical parameters of the pump. The final target of the parametric study is to reach an optimized configuration for the jet pump, i.e., to elaborate the mass flow rate, to generate the pressure head, to obtain a static pressure at driver inlet as low as possible to facilitate the design of the driver's centrifugal pump, to maintain the velocity at the tip of the driver lower than 15 m/s (and in general as low as possible), to have a uniform velocity profile at the diffuser outlet (with a maximum value equal to 3.5 m/s) and finally to respect the geometrical limitations and to maintain a good performance in terms of *N*, defined as:

$$N = \frac{P_{diffuser} - P_{suction}}{P_{inlet\ driver} - P_{diffuser}} \tag{1}$$

and of the ratio *M* between the mass flow rate of the fluid at suction (Q_2 vs. the mass flow rate at driver Q_1):

$$M = \frac{Q_2}{Q_1} \tag{2}$$

Several different geometries and Boundary Conditions have been tested in the parametric study (reported in [15]). The optimal performance, according to the geometrical specifications in terms of maximum size allowed, has been achieved at the conditions reported in Table 4, compared with the reference case derived by the theoretical design with the water jet pump parameters: the optimal configuration has been reached essentially increasing the diffuser length and the nozzle diameter.

Table 4. Comparison conditions for reference case and optimal performance.

Case	$\dot{m}_{suction}$ (kg/s)	$\dot{m}_{driver}$ (kg/s)	M	N	$P_{tot}{}^{suction}$ (bar)	$P_{tot}{}^{driver}$ (bar)
Reference case	2202	1250	1.76	0.229	1.63	26.3
Optimal case	2010	1310	1.53	0.28	1.63	23

The velocity (magnitude) vectors and the contour plot of the velocity (magnitude) in the mid-plane section of the jet pump are shown in Figures 5 and 6, respectively.

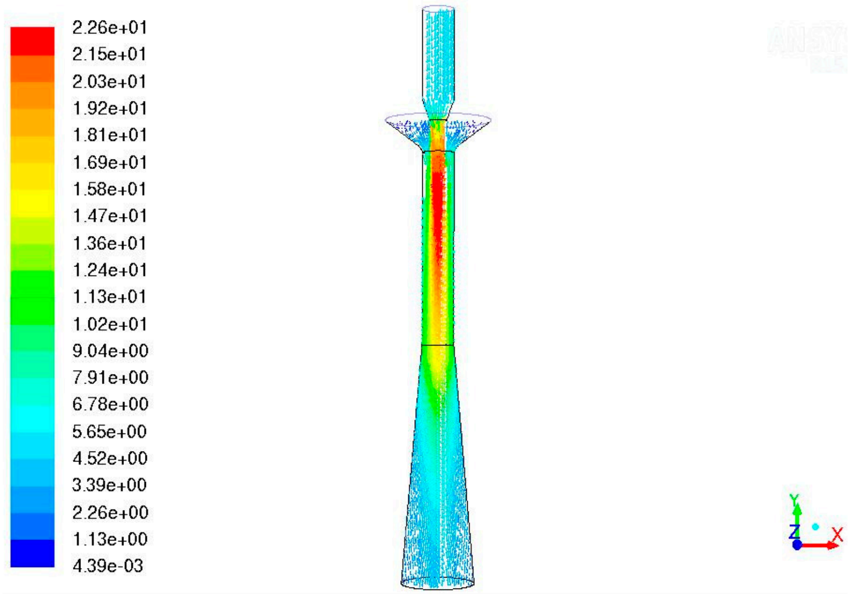


Figure 5. Velocity vectors (magnitude).

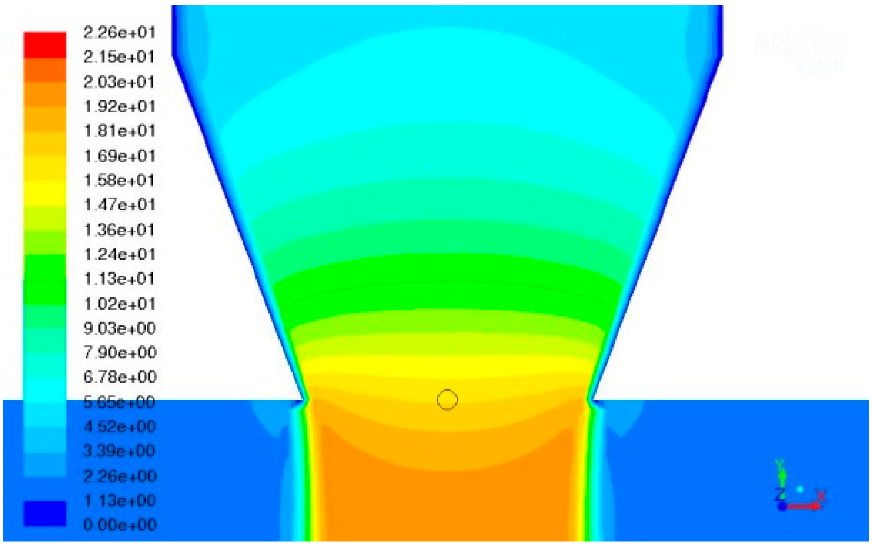


Figure 6. Contours of nozzle velocity (magnitude).

While the jet pump meets the requirements, two major problems prevent its use in ALFRED:

- The liquid lead velocity of 15 m/s at the driver's tip. While present technology supplies various surface treatments to deal with the erosion phenomena caused by lead, the long-term sustainability of a jet pump working with a driver requiring a maximum velocity of 15 m/s is at least questionable. It is not currently possible to give assurance that this device could respect the durability in these conditions without structural damages
- An operative pressure of at least 23 bar for the driver. The authors are not aware of any general-purpose or especially engineered pump elaborating liquid lead and producing such a pressure. Possibly, the design of such a pump is of the same order of technological difficulty as the jet pump it is supposed to drive.

3.2. Theoretical and CFD Simulation of the Archimedean Pump

As with the jet pump, the reasons behind the detailed analysis of an Archimedean pump as primary pump for a nuclear reactor are related with the safety requirements of a GEN-IV reactor:

- Enabling the coolant NC in accidental or only locked rotor conditions
- Removing the heat from the core even in the case of failure of any (Design Basis Scenario) or all (Station Black-out Scenario) of the eight pumps.

The objective of the modeling of the Archimedean pump is to determine if the device can generate the required increase of pressure at normal operation conditions and if the pressure loss in NC conditions does not prevent the establishment of the NC itself.

The Archimedean (or screw pump) is the oldest type of rotating pump. Even though this pump was invented in ancient times, it has been improved throughout time and still today it is widely used. The Archimedean pump is used mainly for moving fluids from a lower to higher level. In the specific application for ALFRED, the Archimedean pump should have the same diameter as the jet pump, pumping the liquid lead downward and having the suction side in the pool right below the free surface. The detailed 3D CFD analysis has been performed using the established package ANSYS CFX [13]. In [19] an in-depth analysis of the Archimedean pump evolving liquid lead for ALFRED is presented.

The same requirements as with the jet pump have been applied: the pump is required to evolve 6450 kg/s of mass flow rate (the reactor's geometry using the Archimedean pump envisioning 4 Main Circulation Pumps) and to generate 1.5 bar of differential pressure [6]. The imposed external constraints (due to reactor geometrical design and/or compatibility between lead and structural materials) of the design are:

- Rotational speed: the velocity inside the pump shall not exceed 10 m/s, due to erosion phenomena
- Pump duct's diameter: the diameter shall be smaller than 1.2 m, to limit the diameter of the vessel, that contain each component
- Duct's pump length: about 5 m from the pool's free surface to the location of the impeller, due to safety requirements in terms of possible entrainment of gas in the flow, which in the case this gas reaches the core it could produce unexpected positive reactivity peak.

Figure 7 shows that, from the kinematic point of view, the traditional Archimedean pump with straight cylindrical beam can be considered as an axial pump with straight blades. From a theoretical analysis it can be demonstrated that, this pump cannot generate work because the velocity triangles in the sections in screw and out are not different. Indeed, in the non-viscous case and according to the canonical equation [19], if the velocity triangle does not change between the inlet and outlet sections the (total and static) pressure remains unchanged. So, in order to generate the required increase of pressure, the pumping device has to deflect the flow field at outlet (i.e., the velocity triangle at the out section) with respect to the inlet conditions (i.e., the velocity triangle at the in section).

There are two viable possibilities to deflect the flow between the in screw and out screw sections:

- By changing the axial pitch of the screw (Figure 8). In this case, the relative velocity W is reduced inside the device and hence, on the basis of the canonical equation [19], the static pressure increases moving from the inlet to the outlet pump sections.
- By deflecting the flow via a change of the hub diameter of the screw pump (Figure 9). Doing so, the flow increases its absolute velocity moving from the section in bulb to the section in screw. Then, according to the canonical equations [19], the static pressure decreases in this portion of the pump, although passing from the section in screw to the section out screw the static pressure increases more than the previous decrease. So, this Archimedean pump with variable hub diameter can generate the required increase of pressure.

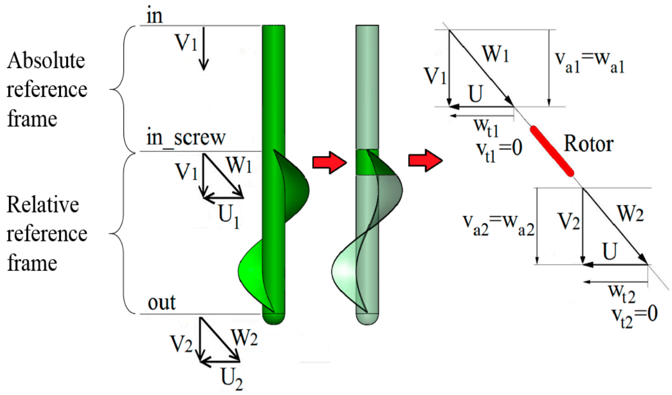


Figure 7. Velocity triangle at the in and out sections.

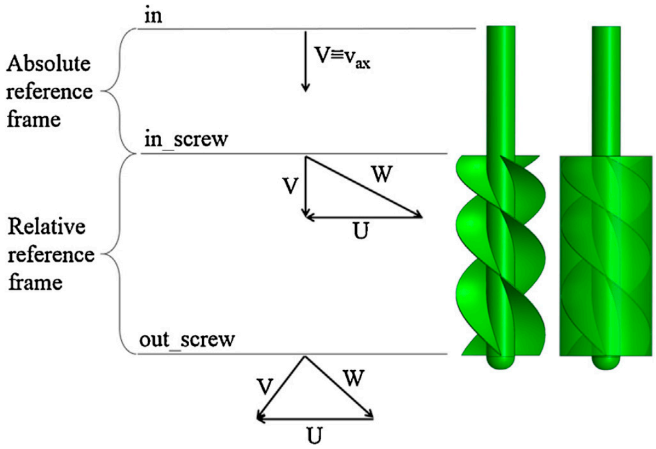


Figure 8. Screw pump with increasing pitch and velocity triangles.

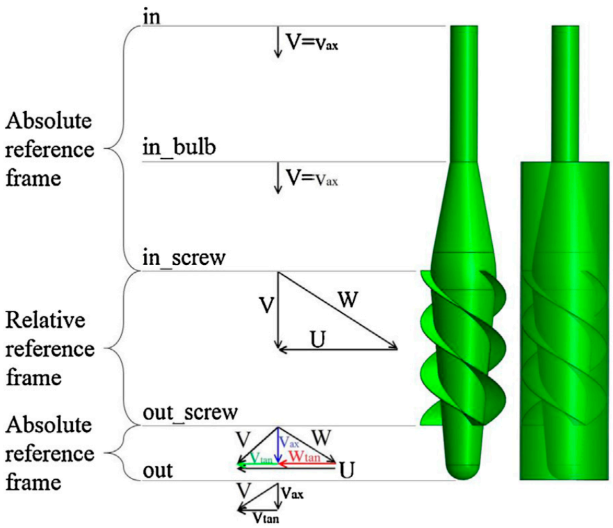


Figure 9. Screw pump with variable hub diameter and velocity triangles.

Both geometries present an original design, which, at the best of Authors' knowledge, have not been analyzed before as per the use in NPPs. Because of manufacturability considerations with respect to the variable pitch screw, this analysis focused on the fixed-pitch screw pump with variable diameter hub. An optimization study has been performed [19] for many geometries and Boundary Conditions and the results for the optimal design, meeting the specifications and the Boundary Conditions, are presented hereunder.

In a very complex geometry such as the variable diameter hub, screw pump, each parameter (e.g., the length/angle of each variable diameter hub, the rotational regime (RPM), the pitch of the helix/angle of attack) has a major effect on the pump performance and all of them should be optimized together to reach the optimal performance.

A rotational speed of 315 RPM has been determined to represent the optimal trade-off between the need to have a low peripheral velocity and the need to transfer energy to the fluid preventing any flow separation, where the latter is also dependent on the length of the hub from the section out_screw to the section out. The differential static pressure for the new design is 1.2 bar while the differential total pressure is 2.2 bar.

The flow field at design point is shown in Figure 10. The differential total pressure vs. the mass flow rate curve for the optimal geometry simulations in off-design conditions is shown in Figure 11.

As stated above, a key requirement for the design of the pump is to not prevent or to impairing the establishment of the flow at NC conditions. Therefore, a major emphasis has been applied to combining a design maximizing the energy transferred to the coolant in Normal Operation Conditions and minimizing the pressure loss at NC conditions. The pressure loss of the optimal design of the pump is 0.04 bar at a NC flow rate of 644 kg/s. Figure 12 shows the key characteristics of the flow at NC conditions. Figure 13 shows the velocity streamlines on the frusto-conical surface of the rotor in NC (off-design) conditions. In spite of a non-negligible change in the mass flow rate, the flow field does not show any detachment from the surface, so minimizing any undesired performance degradation.

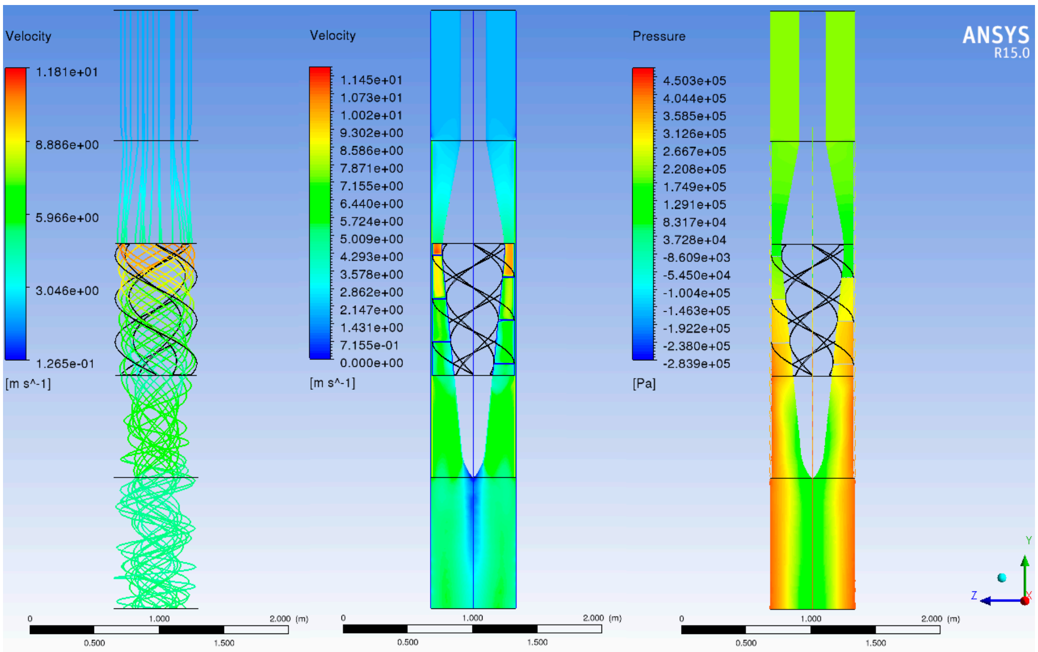


Figure 10. Optimal design of the Archimedean pump: velocity streamlines (**Left**), velocity contours (**Middle**) and static pressure contours (**Right**) on a longitudinal plane.