Design optimisation of a nanofluid injection system for LOCA events in a nuclear power plant

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Abstract. The safety issues inside a Nuclear Power Plant (NPP) are encompassing their capacity to ensure the heat sink, meaning the capacity of the systems to release the heat from the rector to the environment. The nanofluids having good heat transfer properties, are recommended to be used in such applications. The paper is solving the following scenario: considering the Safety Injection tank and the Nanofluid injection Tank, and considering the Nanofluid injection Tank filled with a 10% alumina-water nanofluid, how can we select the best design of the connecting point between the pipes of the SIT and the Nanofluid Tank and the pressures inside of any of these tanks in order to have the biggest density of nanoparticles leaving the tanks toward the cold leg. In conclusion the biggest influence over the rate of disposal of the nanofluid inside ECCS is that of the pressure inside the SIT followed in order by the injection pipe diameter and the pressure inside the nanofluid tank. The optimum balance of these three design parameters may be reached following the procedure shown in this paper.

1. Introduction
The safety issues inside a Nuclear Power Plant (NPP) are encompassing their capacity to ensure the heat sink, meaning the capacity of the systems to release the heat from the rector to the environment. The nanofluids having good heat transfer properties are recommended to be used in such applications [1].

Some extensive studies to use the nanofluids in the emergency core cooling systems (ECCSs) were conducted in order to increase the critical heat flux (CHF) in the case of loss of coolant accidents (LOCAs).

One issue for this kind of applications is regarding the compatibility of the conventional systems used in NPP with the advent of nanofluid technology. The fact is that the ECCS system has to be studied in terms of functional integration requirements, reliability and performance.

For short LOCA accident is defined as a failure of the reactor coolant system (RCS) pipelines of a NPP [1]. These accidents are regarded as very serious since if not tackled, it leads to the core meltdown.

The nanofluids were for the first time defined as colloidal dispersions inside a base fluid, in 1995, by Choi,[2], and since the nanofluid technology continued to evolve during mainly the past decade.

The nanofluid qualities are:
(1) they are increasing the thermal conductivity (approx. 150%),
(2) they are increasing the single-phase heat transfer coefficient (approx. 60%),
they are increasing the critical heat flux with extended nucleate boiling regime (approx. 200%), and

Such a nanofluid-engineered ECCS is made out of a borated water storage and a nanofluid storage (Figure 1). The tank is containing borated water at 40 bar pressure and it is shadowed by a nanofluid storage tank containing the nanofluid to atmospheric pressure or else to a higher pressure.

During normal NPP operation the borated tank and the nanofluid one are isolated via a stopper. Following the LOCA accident the stopper is moving and the SIT tank nitrogen pressure is invading the nanoparticle storage tank and the nanofluid is injected inside RCS along with the borate solution (Fig.1).

The nanofluid consists of alumina nanoparticles (Al2O3) and water, and the nanoparticles are assumed to be well dispersed within the base fluid (water). Furthermore, the nanofluid can be regarded and analysed as a single-phase fluid because the nanoparticles are ultrafine and they can be fluidized easily [3].

The physical properties of water and Al2O3 are shown in Table 1 [3], and the effective physical properties of the nanofluids are obtained from the physical properties of the base fluid (water) and the nanoparticles of alumina, respectively. The alumina-water nanofluid is expected to have the enhanced heat transfer characteristics since the thermal conductivity of alumina is much higher than that of water.

![Figure 1. The nanofluid injection system, [1].](image)

| Concentration (%) | Density (kg/m³) | Viscosity (Ns/m²) | Specific heat (J/kgK) | Conductivity (W/mK) | Increasing rates of conductivity |
|-------------------|----------------|------------------|----------------------|--------------------|-------------------------------|

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The paper is solving the following scenario: considering the Safety Injection tank and the Nanofluid injection Tank as shown in Figure 1, and considering the Nanofluid injection Tank filled with a 10% alumina-water nanofluid, how can we select the best design of the connecting point between the pipes of the SIT and the Nanofluid Tank and the pressures inside of any of these tanks in order to have the biggest density of nanoparticles leaving the tanks toward the cold leg.

In order to solve the above stated problem, we will use Ansys CFX for CFD calculations and Response Surface Optimisation module of Ansys to tackle with the optimisation problem.

Response surface methodology (RSM) is by definition a sum of mathematical and statistical methods to construct and analyse empirical models.

The goal of such a methodology is to optimise some output variables influenced by a set of input variables by running some sets of numerical experiments. A run is defined as changing the input variables and study the effect of change over the output variables. The result of those sets of run are the Response Surfaces.

2. Materials and methods

2.1 The CAD Model

In order to proceed with the FEA (Finite Element Analysis) simulation and optimisation, it is a must to generate the CAD (Computer Aided Design) model. In order to do this the SolidWorks 2015 software was deployed. The joint point of the SIT and Nanofluid Tank is looking as seen in the figure below:

![Figure 2. CAD Model in SolidWorks 2015 with optimisation parameters.](image)

As seen in the figure 2 the model comprises a piece of pipe coming from SIT where the pressure is 40 bar, joining another piece of injection pipe coming from the Nanofluid Tank where the pressure is 55 bar. This system concept is different from the concept shown in Fig.1 considering the
Nanofluid Tank to get pressure from another separate nitrogen tank pressurized with 55 bar. Therefore, there is no link between the SIT and the Nanofluid Tank.

The SIT pipe has the diameter of 200 mm and the pipe of Nanofluid Tank has 40 mm (for the initial model).

The input parameters for the design optimisation process are (with values for the initial model):
- **InjectorDiam (P2)** is the Diameter of the Nanofluid Tank (40 mm),
- **InjectorAngle (P3)** is the angle between Nanofluid Tank injection pipe and the SIT pipe (450),
- **InletPressureLOCA (P7)** is the pressure inside the SIT (40 bar),
- **InletPressureNano (P8)** is the pressure inside the Nanofluid Tank (55 bar).

To be noted that the pressure inside the EECS in case of LOCA is deemed to be 37 bar.

The output parameter to be optimised is **VolumeFractionNanofluid (P6)** which is the volume fraction of nanofluid leaving the LOCA pipe as seen in figure 2.

The figure 3 is showing these parameters:

| Outlines of All Parameters |     |     |     |
|----------------------------|-----|-----|-----|
| A  | ID | B   | C   | D   |
| 1  |    | 1   |     |     |
| 2  |    |     |     |     |
| 3  | Input Parameters | Input Parameters | Value | Unit |
| 4  | P2 | InjectorDiam | 40 | mm |
| 5  | P3 | InjectorAngle | 0.7854 | radian |
| 6  | P7 | InletPressureLOCA | 4 | MPa |
| 7  | P8 | InletPressureNano | 5.5 | MPa |
| 8  |     | Empty input parameter | New name | New expression |
| 9  |     |     |     |     |
| 10 | Fluid Flow (CFX) (LU) | Fluid Flow (CFX) (LU) |     |     |
| 11 | P6 | VolumeFractionNanofluid | 0.0328% |     |
| 12 |     |     |     |     |

**Figure 3.** Design optimisation parameters.

2.2 **The FEA Model**

First of all, in FEA model the material properties are to be defined. Inside the SIT will be water with its well-known properties and inside the Nanofluid Tank is the nanofluid with alumina concentration of 10% as defined in table 1. The strategy of FEA simulation is considering the CFX module of Ansys Workbench 15 with multiphase input since the two fluids have different properties.

The finite volumes meshing is given in the figure 4 comprising 10230 elements with 12776 nodes.

The finite elements are hexahedral type suited for CFD simulation and their quality is deemed good as seen in the figure 5.

![Figure 4. Finite volumes Meshing.](image1)

![Figure 5. Finite volumes elements quality.](image2)
The boundary conditions are those already stated simulating the LOCA event to the outlet surface, inside the SIT and Nanofluid Tank (see figure 6).

The Analysis Type is Steady State with 1000 iterations imposed for the convergence of the results. After solving we have seen that only 253 iterations were enough for convergence.

3. Results and discussion

3.1 The Initial Model CFD Simulation Results
After reaching the convergence the following results were calculated:

**The total pressure**

The pressure distribution in figure 7 is showing that in case of LOCA event the SIT and the Nanofluid Tank is starting to “pump” fluids in the ECCS in order to compensate the loss of the cooling agent.

**The nanofluid superficial velocity**

The maximum velocity of the nanofluid migrating into ECCS is 39.97 m/sec reached inside the injection pipe as seen in the figure 8. The nanofluid is propelled with this velocity inside the EECS due to the Nanofluid Tank pressure of 55 bar.

![Figure 6. The boundary conditions.](image)

![Figure 7. The total pressure fields distribution inside the fluid domain.](image)

![Figure 8. The nanofluid superficial velocity fields distribution inside the fluid domain.](image)
The density
Since the nanofluid is denser than the injected water from the SIT, the density is reaching a maximum of 1.294e3 kg/m³ inside the injection pipe and then is slowly diluting toward the Cold leg entrance.

The Nanofluid Volume Fraction
The nanofluid volume fraction in the output parameter to be optimised and that is because the bigger is this volume fraction at the exit surface (Fig.10), the biggest is the quantity of nanofluid injected in ECCS and the impact on substituting the lost coolant is improved. The value calculated as average for the exit surface is 0.0325 meaning that only 3.25% of the injected fluid is comprising nanofluid.

3.2 Design Optimization
The module of RS optimisation is establishing 26 design points where the 4 input parameters are statistically variated using the algorithm of the Central Composite design. The local sensitivities of the output parameter as a function of the input parameters are given in the figure 11.

From the graph, we may conclude that the most influential parameter is inlet pressure inside the SIT (with green on figure11), the next most influential is the injection pipe diameter of the injection pipe (red), almost equal in influence with the pressure inside the nanofluid tank (blue). The impact of injection pipe angle variation (yellow) is almost none so that the injection pipe may join the LOCA pipe at 900.

Some of the design optimum response surfaces are shown in the figure 12.

In the figure 12, we may see how looks the RS for the diameter of the injection nanofluid pipe. The output parameter varies almost linearly with this diameter in the direction that the bigger is this diameter the more nanofluid is injected in ECCS. This is a mathematical demonstration of an almost common sense engineering conclusion.
On the other hand, the more pressure is inside the SIT, the less nanofluid is injected inside the ECCS. To make this pressure lower is not always feasible since the pressure inside this tank is dictated by the injection phases in case of LOCA event.

The pressure inside the nanofluid injection tank is increasing the releasing rate of the nanofluid inside ECCS, in an almost linear fashion as seen in figure 14.

By placing the condition that the output parameter namely the nanofluid volume fraction to be at maximum, the software is proposing three best candidates for the designer perusal. We may choose the first Candidate marked with yellow on the following table:

| Candidate | P2 – Injector Diam (mm) | P3 – Injector Angle (radian) | P7 – Inlet Pressure LOCA (MPa) | P8 – Inlet Pressure Nano (MPa) |
|-----------|--------------------------|-----------------------------|-----------------------------|-----------------------------|
| Point 1   | 48.7727                  | 0.759315                    | 3.6                         | 5.687264                    |
The Optimized Model CFD Analysis

After reaching the convergence for the optimum candidate, the following results were calculated:

The total pressure

The pressure distribution in figure 15 is showing that in case of LOCA event the SIT and the Nanofluid Tank is starting to “pump” fluids in the ECCS in order to compensate the loss of the cooling agent. The influence of a bigger nanofluid tank pressure is by now visible since the nanofluid is somehow “taking-over” the function of the SIT for a while injecting a massive amount of nanofluid inside ECCS in this first stage of LOCA.

The nanofluid superficial velocity

The maximum velocity of the nanofluid migrating into ECCS is 54.27 m/sec reached inside the injection pipe as seen in the Fig.8. The nanofluid is propelled with this velocity inside the EECS due to the Nanofluid Tank pressure of 56.8 bar. Since the SIT pressure for the optimised model is 36 bar, the nanofluid is injected inside ECCS with a bigger speed than in the initial scenario.

The density

Since the nanofluid is denser than the injected water from the SIT, the density is reaching a maximum of 1.294e3 kg/m3 inside the injection pipe and then is slowly diluting toward the Cold leg entrance. The density distribution is showing that in this first stage of LOCA the nanofluid injection is prevailing.

The Nanofluid Volume Fraction

The value calculated as average for the exit surface of the optimised model is 0.684 meaning that only 68.4% of the injected fluid is comprising nanofluid. So for the first stage of LOCA event the massive injection of nanofluid is deemed to ease the heat conduction of the coolant agent.
4. Conclusions

All the conclusions below should be cautiously placed inside the design philosophy and LOCA event mitigation scenario of each nuclear power plant.

Whether the designer has in mind firstly to kill the nuclear reaction for massive LOCA then the solution proposed by other authors is the best. But for small LOCA the deployment of a nanofluid tank separately actuated by an azot tank with a superior pressure than that of SIT, may be a better choice since increasing the heat sink may be more useful than killing the reaction.

In conclusion the biggest influence over the rate of disposal of the nanofluid inside ECCS is that of the pressure inside the SIT followed in order by the injection pipe diameter and the pressure inside the nanofluid tank. The optimum balance of these three design parameters may be reached following the procedure shown in this paper.

The optimised nanofluid injection system should look like in figure 19.

References

[1] Kang M and Jee C 2011 Design process of the nanofluid injection mechanism in nuclear power plants, Nanoscale Research Letters.
[2] Choi S 1995 Enhancing thermal conductivity of fluids with nanoparticles. Developments and Applications of Non-Newtonian Flows New York: ASME, 99-105, FED-Vol.23.
[3] Choi J and Zhang Y 2012 Numerical simulation of laminar forced convection heat transfer of Al2O3 nanofluid in a pipe with return bend, International Journal of Thermal Sciences, 55.