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Investigation of Reverse Flow Restriction Device to Mitigate Fuel Dryout during BWR Loss of Coolant Accidents

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Abstract - *This paper analyzes a new method for preventing boiling water reactor fuel damage due to the Loss of Coolant Accidents (LOCA). The method is about using a device called the Reverse Flow Restriction Device (RFRD) at the inlet of fuel bundles in the core to prevent coolant loss from the bundle inlet due to the reverse flow after a large break in the recirculation loop. The device allows for flow in the forward direction which occurs during normal operation, while after the break, the RFRD device changes its status to prevent reverse flow. In this paper, a detailed simulation of LOCA has been carried out by U.S.NRC's TRACE code to investigate the effect of RFRD on the flow rate as well as peak clad temperature of the BWR fuel bundles during two different LOCA scenarios, namely, large break LOCA (100% LOCA) and double-ended guillotine break (200% LOCA). The results demonstrated that the device could substantially block flow reversal in fuel bundles during LOCA, allowing for coolant to remain in the core during the coolant blowdown phase. The device is capable of retaining additional cooling water later after activating the emergency systems, which maintains the peak clad temperature at lower levels. Moreover, the RFRD achieved the reflood phase (when the saturation temperature of the clad is restored) earlier than without the RFRD. Sensitivity results for the friction coefficient demonstrated that for LOCA a high reverse flow friction coefficient is needed and hence the RFRD should be well-fitted to the lower tie plate to be able to sustain the high pressure caused by the large coolant flow during the blowdown phase of LOCA.*

I. INTRODUCTION

Boiling water reactors (BWRs) like Pressurized Water Reactors (PWRs) are subjected to Loss of Coolant Accidents (LOCA), which result from a break in one of the primary pipes of the recirculation loop. If a break occurs in the suction side of the recirculation pump, a LOCA begins and the coolant starts to flow out from the core due to the break, resulting in increased fuel temperature which could lead to fuel damage and core melt if inadequate cooling is provided to the core. Once the break occurs, the reactor scrams and the core starts depressurization. Reverse flow in the broken loop occurs, and the coolant will be lost from the bundle inlet. In general, there are three phases of a LOCA, namely, blowdown, refill, and reflood phases. During blowdown, reactor pressure and coolant inventory decrease rapidly, resulting in an increase in fuel cladding temperature, and the core becomes uncovered. During the blowdown phase, High Pressure Core Injection (HPCI) operates to remove the heat but at a small flow rate because of the high core pressure. When the core pressure reaches lower levels the refill phase starts, where Low Pressure Core Injection (LPCI) and core sprays are functioning to provide massive amounts of coolant to remove the heat from the core. Finally, the reflood phase begins when the lower plenum is refilled with the emergency water and the fuel bundles begin to cool from bottom to top. This phase is also characterized by retaining the saturation temperature of the cladding as it quenches. The LOCA scenario ends when all the heat is removed from the core and the fuel cools down to its saturation temperature [1].

As LOCA is a challenging accident in the nuclear industry, significant research has been conducted in this area to investigate the core behavior during LOCA, as well as the consequences of such accidents. Computational codes have been developed to analyze LOCA such as TRACE. TRACE [2][3] is the latest best-estimate reactor systems code. It was developed by the U.S. Nuclear Regulatory Commission (U.S.NRC) for analyzing steady state and transient thermal-hydraulics systems for light water reactors. U.S.NRC combined its main four codes (TRAC-P, TRAC-B, RELAP5, and RAMONA) into one modernized and advanced computational code. Specifically, TRACE has been designed to perform best-estimate analyses of LOCAs, but it can simulate other phenomena in Light Water Reactors (LWRs) like operational transients, Anticipated Transients Without Scram (ATWS), two-phase flow, heat transfer problems, and others.

Queral et al. [4] used TRACE to model Large Break LOCA (LBLOCA) in AP1000 to validate the Westinghouse results and to investigate the effectiveness of AP1000 in mitigating LBLOCA accidents. The study concluded that the TRACE results showed lower peak clad temperatures (PCT) than those calculated by Westinghouse, which proves that AP1000 passive safety systems can mitigate LBLOCA accidents within a safety margin. A similar study by Montero-Mayorga et al. [5] but for Small Break LOCA (SBLOCA) was done using TRACE on AP1000. The results obtained by this study captured similar trends of various SBLOCA sizes as reported by Westinghouse with some differences between TRACE predictions and Westinghouse results. The reason for these differences could be due to the conservative assumptions used by Westinghouse in modeling of LOCA. TRACE has been used by Chen et al. [6] to study alternate mitigation strategies for a BWR LOCA with station blackout (loss of onsite and offsite power) similar to the accident that occurred at Fukushima. The new mitigation strategies adopt the turbine driven pumps and high pressure injection systems to maintain sufficient water level within the core before the pressure is released. The study concluded that these strategies are effective at obtaining earlier reactor water recovery and a lower peak cladding temperature in the extreme event of station blackout with a LOCA. In another study, TRACE has been used to validate the experimental results for a LOCA. Hu et al., [7] compared the predictions of the TRACE code including the pressure, flow rate, and core temperature with the experimental results for different LOCA scenarios and the study found that TRACE can reproduce the experimental results well.

In this paper, a new device called Reverse Flow Restriction Device (RFRD) [8][9] is introduced and tested by simulation to demonstrate its effect in reducing the PCT during the progression of a LOCA and hence increasing the safety of BWRs. The RFRD device was successfully shown to prevent fuel Dryout during BWR instability accidents as the device proved to reduce the magnitude of BWR oscillations as well as the clad temperature during the rewet-dryout period [9][10]. In this paper, a previously tested TRACE model [11][12] has been used to validate the potential effect of restricting the flow in the downward direction on reducing the clad temperature during LOCA. This study could be valuable if it proves that the clad temperature can be reduced during progression of the LOCA accident, which will increase the cooling efficiency of the safety systems because the fuel will be kept in low temperatures.

Consequently, TRACE has been selected because it has many features that fulfill the requirements of this study including:

- TRACE is designed especially for LOCA modeling in LWRs.
- TRACE is capable of simulating both the forward and reverse flow with the option of controlling the friction coefficient for both directions.
- TRACE is accurate in predicting clad temperature excursion and flow rate in case of exceeding critical heat flux conditions, which means that the effect of using the device can be demonstrated.

The remaining sections of this paper are organized as follows: the description of the proposed device along with the TRACE model used in this study are presented in Section II. Section III presents the results obtained from this study along with the discussion of the results. The conclusions of this work and recommendations for future work are presented in the Section IV.

II. DESCRIPTION OF THE WORK

Farawila [8] in his paper recommended a device to restrict the flow in the reverse direction to minimize the oscillation magnitude in BWR's instability events. The device has been tested in BWR instability accidents in these references [9][10]. For LOCA, the objective of the device is to maintain coolant levels within the core. The RFRD is introduced to the lower tie plate of the fuel assembly (bundle) to act as a check valve. Fig. 1 depicts the lower tie plate of a fuel assembly for BWR with the proposed device equipped. The RFRD consists of a grid of check valves for each fuel channel inside the fuel assembly. The sketch shows that the RFRD consists of two parallel plates where each plate has holes forming a cavity inside, and the screen is free to move between the plates.

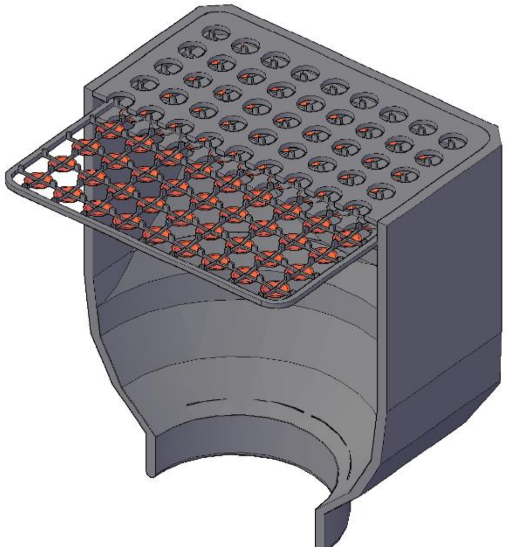


Fig. 1. Lower tie plate of the fuel bundle equipped with RFRD to prevent the reverse flow

Fig. 2 shows an isometric sketch of the screen that moves between the plates during the flow direction changes. The screen has a grid structure and it consists of an array of disks aligned with the holes in the plates. The holes in the grid have tabs to keep the forward flow unobstructed, while during the reverse flow the screen goes down blocking the holes beneath it. The disks should be well-fitted to the screen to assure a high friction factor in the reverse direction to block the flow and to avoid releasing of loose parts during large blowdown of water (e.g. LBLOCA). The device shown in Fig. 2 is designed for 9x9 type of BWR fuel bundles.

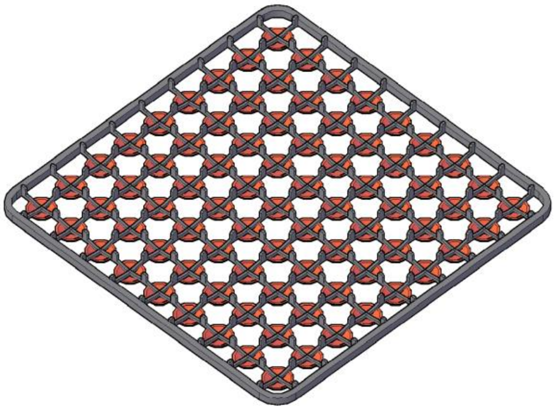
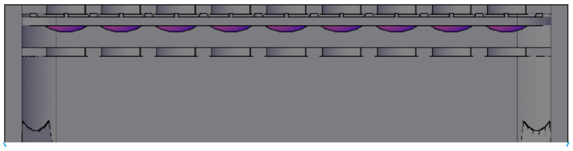
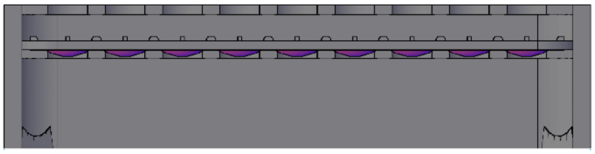


Fig. 2. Isometric sketch of the RFRD

During forward flow, the coolant flow exerts a force to lift the screen into the upper plate. In reverse flow, the pressure exerted by the coolant disappears and hence the screen drops to the down position and rests against the lower plate (See Fig. 3). The floating screen switches between the up (open) and down (closed) position based on the flow direction and this distance is very small to eliminate high speed movement which means the opening and closure of the flow path are not abrupt but rather smooth. Fig. 3 shows the floating screen between two parallel plates. On the top of the figure the screen is in the up position which is the normal position with the flow in the upward direction, while on the bottom, it shows the screen in the down position to prevent the reverse flow which occurs during accident conditions.



Forward Flow is Allowed



Reverse Flow is Prevented

Fig. 3. Position of the RFRD against the upward and downward (reverse) flow

To validate the potential effect of the proposed device on reducing the clad temperature during LOCA, a BWR TRACE model has been developed for this study. Unfortunately, TRACE does not provide flexibility in geometry modeling to model such a device, because TRACE is a component-wise code so that the geometry can be built based on a set of components pre-defined in TRACE. However, TRACE allows the user to control the value of the friction coefficient in the reverse direction which is directly connected to the objective of the device. Therefore, if a large friction coefficient is used at the bundle inlet for the reverse flow, the RFRD effect could be simulated in TRACE. In this case, the forward flow is allowed and once the flow reverses in direction, the high friction coefficient will prevent the reverse flow. The fuel channel is divided into 28 axial nodes. The RFRD device is applied by increasing the value of Reverse Flow Friction Coefficient (RFFC) at the first inlet node as this is sufficient to ensure blocking the reverse flow. The reactor vessel is modeled by a 3D vessel component with 15 axial cells, 2 radial cells, and 1 azimuthal sector. Each CHAN component is modeled with 28 uniform axial nodes. Both forward and reverse flow friction coefficients have been added to each channel component to model the RFRD device. The results with and without the RFRD have been calculated using this TRACE model. The nodalization scheme of TRACE model is shown in Fig. 4.

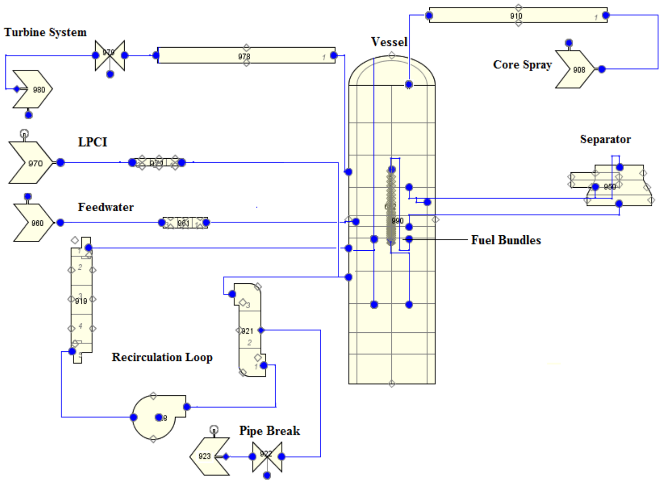


Fig. 4. BWR TRACE model nodalization scheme

As per the nodalization scheme shown in Fig. 4, the TRACE reactor model consists of the following components:

- Reactor vessel represented by VESSEL component.
- 444 fuel bundles represented by 222 BWR CHAN components in one-half core symmetry.
- One recirculation loop has an outtake pipe connected to the downcomer, through which the coolant is redirected to a recirculation pump. The coolant is pumped via the intake pipe to the lower plenum in the vessel.
- LOCA break is connected to the recirculation pipe that is connected to the pump discharge.

The break size is controlled by area fraction of a valve connected directly to the break

- Core sprays and LPCI consist of a FILL and a PIPE component.
- Turbine system consists of a PIPE, a VALVE, and a BREAK to impose a pressure boundary condition.
- Feedwater system consists of a PIPE component and a FILL to impose a flow rate boundary condition.
- One steam separator represented by SEPD component.

An important step for accurate LOCA modeling is how to model the transients, which include all of the changes in operation that occur after the break. This means that some systems should be turned off and other appropriate systems should be activated to mitigate the adverse effects on the fuel. In general, a LOCA is initiated by opening the BREAK component which is connected to the pipe in the recirculation loop through a valve. The initiation of LOCA is set at t = 15s. After 0.5s, control rod banks are inserted to shut down the reactor and the pump is tripped. This is followed by the closure of the feedwater, closure of the turbine valve, and the activation of the emergency cooling systems at low pressures. Table I lists the main events following the LOCA break with the time for each event.

Table I. List of the main events of LOCA base model

Event	**Time**
Break valve open time	15.0 s
Pump trip	15.5 s
CR bank insertion	15.5 s
Closure of feedwater flow	16 s
Closure of turbine valve	17 s
ECCS activation	t @ P≤0.2 MPa

The timing for activating and closing of different systems during LOCA such as feedwater, turbine, and core spray systems should be described. For the turbine valve, it is assumed that the turbine valve receives the signal in 0.2s followed by an additional 0.8s to start the procedure of closing the valve. 0.5s is needed after that to close the turbine valve itself. Closure of feedwater is done in 1s where the feedwater flow is dropped from rated flow to zero. The activation of the emergency systems to cool the reactor fuel is determined by means of the pressure value in the core instead of time. When the pressure inside the core drops to a value of about 2 bar, core sprays and LPCI are activated.

Critical (or choked) flow occurs in cases where fluid moves out of a higher pressure volume at a speed limited only by the speed of sound for fluid. This situation occurs in a LOCA as the break mass flow depends on the condition of the main system and not on the pressure outside, which is the containment pressure. In this work, the choked flow model is activated with default TRACE parameters only at the BREAK component. TRACE simulations consist of two main steps connected through a restart file as follows:
1. Steady-state TRACE thermal-hydraulics simulation for user-defined flow and power conditions. Steady-state results are used as initial conditions for the transient calculations.
2. Transient TRACE calculations using pipe break as initiating event.

In the next section, the results for LOCA simulation when using the RFRD device and without using it are presented.

III. RESULTS

As mentioned before, two LBLOCA cases have been considered in this study: the first is 100% LOCA where the break size is 100% of the recirculation loop flow area. The second case is double-ended guillotine break (also known as 200% LOCA) which is a hypothetical accident that occurs when the recirculation loop pipe attached to the pressure vessel is totally broken into two separate flow paths so that 100% coolant loss occurs in each part.

Simulation results for 100% LOCA model shows that the RFRD device can successfully prevent reverse flow that leads to coolant leakage from the fuel bundle inlet during 100% LOCA. As mentioned before, the RFRD is applied to all core bundles for each LOCA case. Fig. 5 and Fig. 6 show that the flow rate behavior for a hot channel and an average channel during 100% LOCA is nearly the same. Without RFRD, negative flow rate occurs directly after the break as flow rate reaches about -10 kg/s in hot bundle and -5 kg/s in average bundle due to the blowdown phase of the LOCA where the coolant leaks from the break and from the bundle inlet out to the containment. After that, the bundle is left dry with only steam flow for some time until the activation of the core sprays and LPCI. The reverse flow occurs again when the emergency water starts to flow inside the core. However, the RFRD device prevents flow reversal when it is applied to all bundles except at the beginning of the blowdown phase, where insignificant flow reversal is still observed (see Fig. 5 and Fig. 6). The reverse flow has been eliminated after using RFRD for both stages, during blowdown and after the activation of safety systems. Therefore, the effectiveness of the device depends on how much flow reversal happens during the LOCA accident. Therefore, by preventing the leakage through reverse flow, more coolant will stay within the core during blowdown and from the emergency systems which will help to cool the fuel.

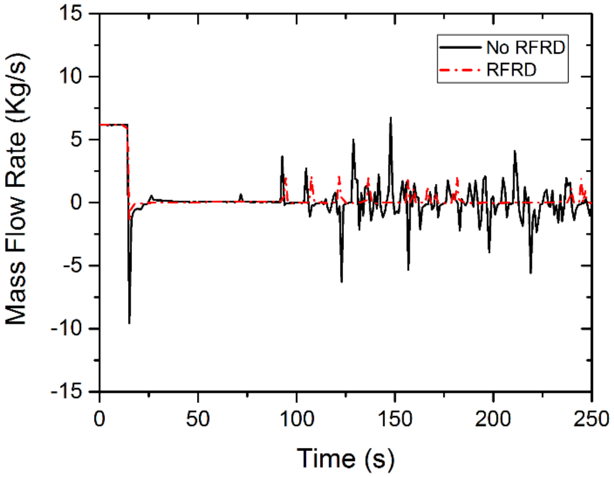


Fig. 5. Bundle flow rate during LBLOCA for a hot bundle

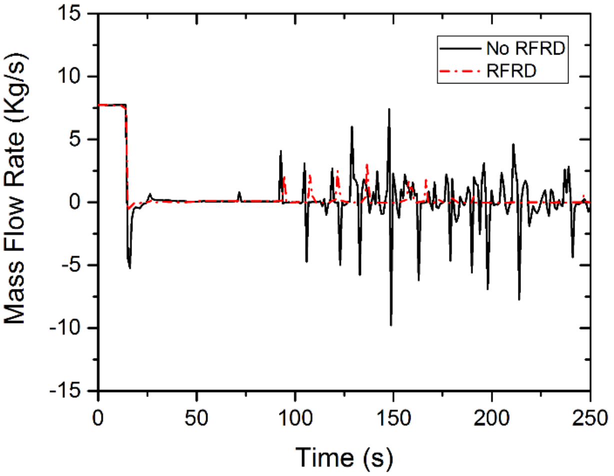


Fig. 6. Bundle flow rate during LBLOCA for a normal bundle

The success of the RFRD device is measured by its effect on the PCT as additional coolant is preserved inside the core. Fig. 7 shows that PCT without using RFRD reaches a value of 1100 K and could lead to fuel damage as it is close to U.S.NRC limit of 2200 ºF (~1480 K). On the other hand, RFRD can reduce the PCT of hot and average bundles to safer levels by increasing the amount of available coolant (see Fig. 7 and Fig. 8). The device has another great advantage as the fuel reaches the reflood period faster when using the RFRD device as the fuel quenches in shorter time than without using the RFRD. This is because as the cladding quenches, the surface becomes wetted, and the saturation temperature of the clad decreases rapidly. The RFRD effect on 100% LOCA can be summarized as:

1- Before the break, the device is already in the up position, no effect is observed (ΔT=0).

2- Directly after the break, the ΔT (difference in PCT between LOCA with and without RFRD) increases sharply since the coolant inventory decreases rapidly (blowdown) without RFRD.

3- After that, ΔT starts to decrease until the activation of the safety systems when RFRD can keep more water inside the core and hence ΔT rises again.

4- RFRD results in earlier quenching for the clad. In this case, ΔT reaches its maximum value since the PCT without RFRD is still high.

The temperature difference between the two cases demonstrates that the device is capable of achieving a reduction up to 600 K for hot channel and up to 250 K for average channel during LBLOCA.

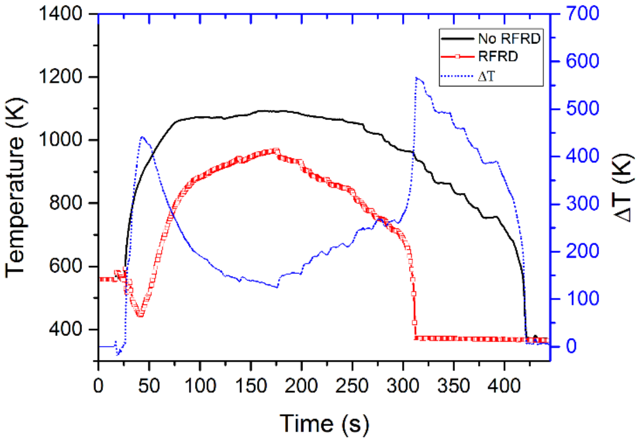


Fig. 7. PCT during 100% LOCA for hot bundle

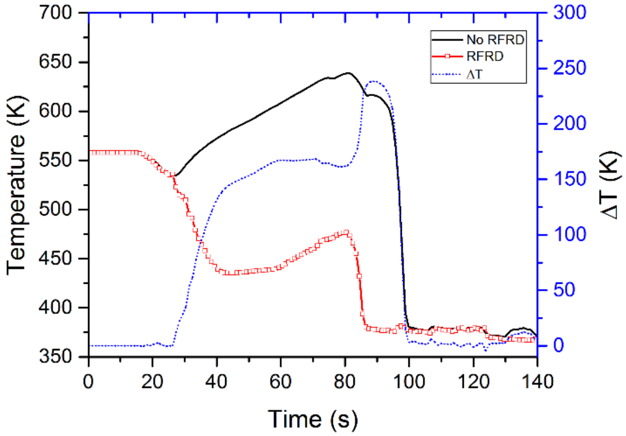


Fig. 8. PCT during 100% LOCA for normal bundle

Additionally, RFRD has negligible effect on other quantities inside the core like the core pressure and the break flow. Fig. 9 shows that the core pressure behavior is similar with and without using the RFRD device and meaning that the device will not affect the core depressurization and hence the safety systems are activated at the same time. Similarly, Fig. 10 demonstrates that the break flow is practically unchanged when using the RFRD since the break is in the recirculation loop and the device has no effect on the flow through the break.

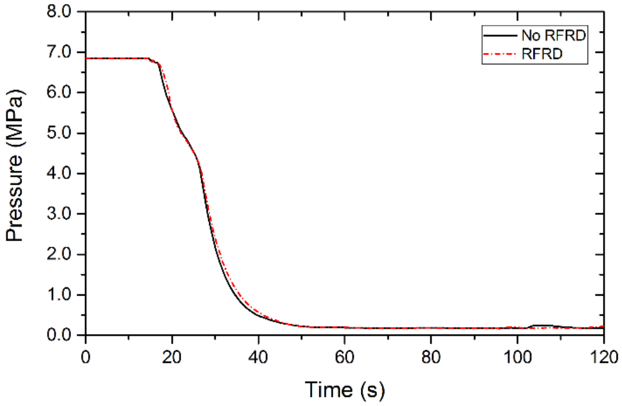


Fig. 9. Core pressure rate during 100% LOCA

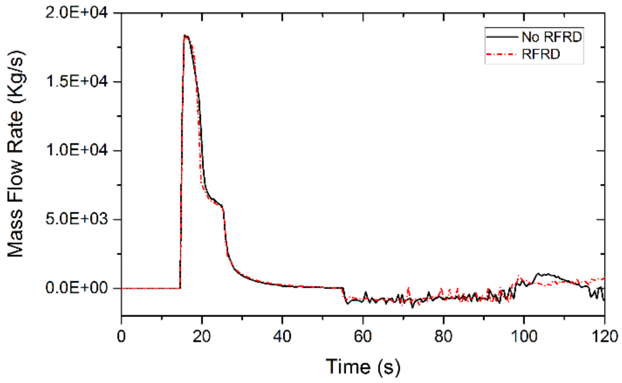


Fig. 10. Break flow rate during 100% LOCA

The scenario for double ended break that has been simulated is 200% double ended guillotine break. The double ended break for BWRs occurs when a guillotine break occurs in the recirculation loop pipe that is attached to the pressure vessel so that the pipe is broken into two separate flow paths. Fig. 11 shows the flow rate and Fig. 12 shows the PCT during the transient of 200% LOCA. The 200% LOCA is characterized by fast depressurization and large blowdown of flow rate to levels even higher than LBLOCA as flow rate drops to -35 kg/s directly after the break. This is because cutting the recirculation pipe into two flow paths will increase the leakage of coolant to large values compared to the smaller breaks, and this makes double ended guillotine break to be the most severe type of LOCA. For PCT, it seems that RFRD is not effective for the first 50s as the PCT with RFRD becomes slightly higher than PCT without RFRD. This result means that the RFRD device would increase the PCT during the double ended break which is an undesirable effect. However, the negative ΔT (difference in PCT between LOCA with and without RFRD) values are considered small and span for only a short time after the break. The momentary small increase in temperature might have occurred because of reduced velocity and heat transfer coefficient. After that, the RFRD device reduced the temperature as ΔT starts to grow from negative values to large positive values. The RFRD device can achieve a positive ΔT up to 550 K during the double-ended break LOCA. Similar to 100% LOCA cases, the cladding saturation temperature is restored faster than the case without using the RFRD device (see Fig. 12).

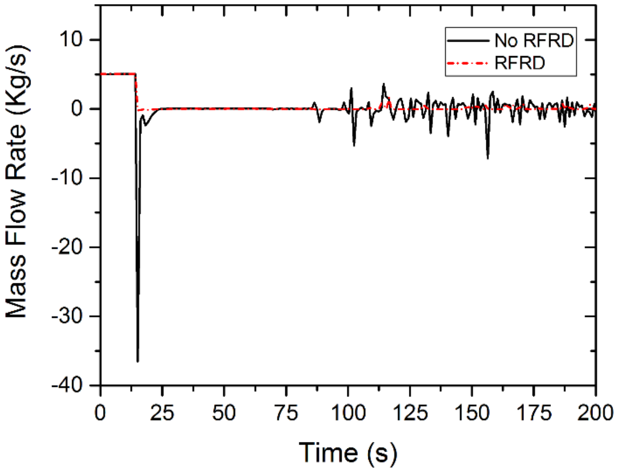


Fig. 11. 200% double-ended guillotine bundle flow

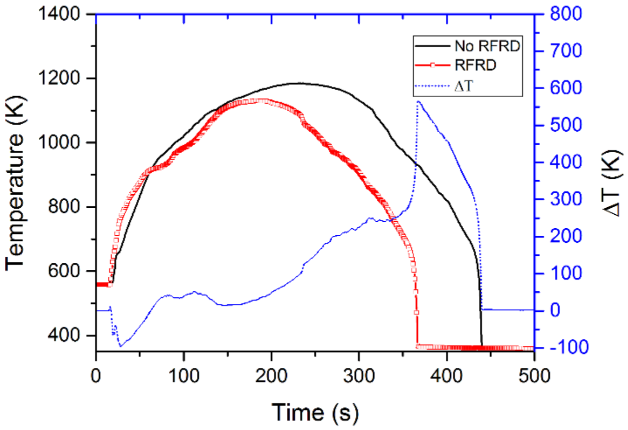


Fig. 12. 200% double-ended guillotine bundle PCT

Therefore, based on the previous analysis, RFRD could decrease the PCT during LOCA progression by approximately 100K for both cases (See Table II). as well the effectiveness of the RFRD device is seen in three areas:

1- The RFRD device can achieve a significant reduction in PCT for the two LBLOCA cases: 100% LOCA and double-ended guillotine break.
2- The RFRD device can achieve a faster quenching of the cladding for the two LBLOCA cases: LBLOCA and double-ended guillotine break.

3- Duration of effectiveness is different for the three cases. For instance, RFRD is effective for the whole period of 100% LOCA. However, for a double-ended guillotine break, RFRD is nearly inactive for the first 200s of the scenario.

Table II. Peak clad temperature values achieved when using and without using the RFRD device.

Case	**PCT without RFRD (K)**	**PCT with RFRD (K)**
100% LBLOCA	1091	962
200% double-ended guillotine	1184	1086

Since the blowdown phase is the most critical moment, as a large amount of water leaks from the core and carries significant momentum, the device should be able to prevent that leakage. Consequently, if the device can prevent the flow leakage during blowdown, it should be able to prevent any other smaller reverse flows. Fig. 13 shows the plot of the bundle flow rate with increasing of RFFC during LOCA. Increasing the value of RFFC from 0 to 50 reduces the reverse flow but it seems to be inadequate, which means that the device should be able to sustain even larger pressure created when the water flows downward. The amount of coolant leakage decreases as RFFC increases, but the relative reduction becomes smaller as RFFC becomes larger. For example, Fig. 13 shows that a relatively small reduction is seen when increasing the RFFC from 400 to 500. In addition, the flow rate becomes insensitive to RFFC when increasing it above 500 as flow rate results for RFFC of 1000 are identical to those obtained by 500. Consequently, the value of 500 for RFFC would be sufficient to achieve a well-restricted flow during LBLOCA.

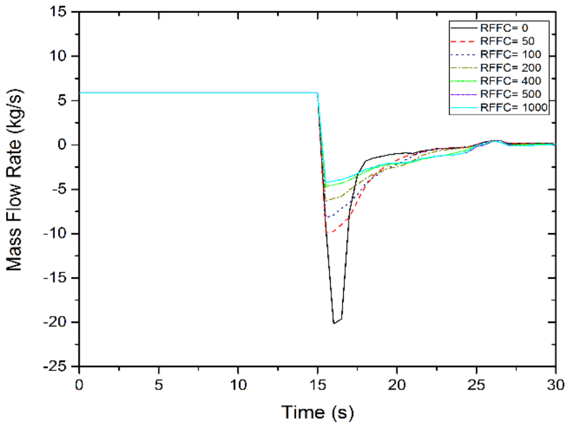


Fig. 13. Bundle flow rate for different values of RFFC during 100% LOCA during the blowdown phase.

The numerical simulations in this study utilize an idealized RFRD by simply introducing flow-direction-dependent friction loss. Characteristics of a real device should be determined in a laboratory, where it is expected that a slightly earlier closure can be achieved upon reaching a small (still upward) mass flow rate in the case the device is gravity operated. No credit is taken for this advantageous earlier closure as the mechanical design features of the device are outside the scope of this article.

IV. CONCLUSIONS

In this study, the TRACE code has been used to study the effect of reverse flow restriction on mitigating the severe LOCA accident consequences. The RFRD device achieved a great capability to keep the fuel safe during LOCA through two stages:

1- Containing the coolant that leaves from the bundle inlet during the blowdown phase, when massive amounts of coolant leaves through the break at the beginning of LOCA.
2- Containing the emergency cooling injection inside the core when the emergency systems are activated.

The RFRD is capable of reducing the PCT to safer levels by maintaining additional coolant inside the core during LOCA. The RFRD is also able to reduce the time needed to reach the reflood phase and quenching when the saturation temperature of the clad is restored. The device demonstrates beneficial capabilities during LBLOCA accidents. Therefore, if the coolant leakage in LOCA accident is reduced by applying flow reversal restriction, there potentially can be a longer coping time during LOCA accidents and the cooling effectiveness of the ECCS will increase.

It is important to mention that the clad temperature as a function of time with the RFRD is not always lower than the corresponding case without the RFRD over the entire problem time, as shown for example in Figure 12. However, the peak clad temperature during the transient is significantly reduced due to using the RFRD.

As a future work, the device can be investigated experimentally in facilities for LOCA to validate the simulation results. Furthermore, this study did not consider the effect of Counter Current Flow Limitation (CCFL) that could occur during LBLOCA which would affect the current results. The CCFL phenomena should be studied when using the RFRD device. Additional studies should be performed to see if RFRD can be useful for other types of accidents, either in a BWR or a PWR, and determine its capability to improve the safety of the reactor during these accidents.

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