

Study on the Application of Temperature Difference in the Evaluation of Pipe Break Size in Recirculation Systems Based on Thermal-hydraulic Model Analysis

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Date: 2025-02-20T00:00:00+00:00

Abstract

This study investigates the temperature difference between recirculation loops following an instantaneous pipeline rupture. The analysis shows that the pipe rupture leads to the conversion of energy in an open system, resulting in the coolant escaping from the broken exhibiting a lower temperature compared to the intact loop. A theoretical model based on energy balance principles effectively explains these temperature differences. Validation through the Modular Accident Analysis Program (MAAP5) simulations and training simulator results confirms that both tools accurately predict temperature changes during station blackout and loss of coolant accident scenarios. This study examines the effects of coolant pipe ruptures on the recirculation system and compares the resulting trends with the simulator data. The model can serve as a foundation for future quantitative research, enabling a deeper understanding of the recirculation system during a break transient period. The use of computer simulation codes will ensure the main phenomena, improve accident management strategies, and establish a basis for future quantitative analyses. And, the results of this study also indicate that the correlation between the temperature difference between pipelines and the break size of pipelines is more strongly assisted by the peak cladding temperature.

Full Text

Study on the Application of Temperature Difference in the Evaluation of Pipe Break Size in Recirculation Systems Based on Thermal-hydraulic Model

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ABSTRACT

This study investigates the temperature difference between recirculation loops following an instantaneous pipeline rupture. The analysis shows that pipe rupture leads to energy conversion in an open system, resulting in coolant escaping from the broken loop exhibiting a lower temperature compared to the intact loop. A theoretical model based on energy balance principles effectively explains these temperature differences. Validation through Modular Accident Analysis Program (MAAP5) simulations and training simulator results confirms that both tools accurately predict temperature changes during station blackout and loss-of-coolant accident scenarios. This study examines the effects of coolant pipe ruptures on the recirculation system and compares the resulting trends with simulator data. The model can serve as a foundation for future quantitative research, enabling deeper understanding of recirculation system behavior during break transients. Computer simulation codes ensure accurate modeling of main phenomena, improve accident management strategies, and establish a basis for future quantitative analyses. The results also indicate that the correlation between pipeline temperature difference and break size provides stronger assistance in determining peak cladding temperature.

Keywords: temperature difference, break size, MAAP5, recirculation loop

INTRODUCTION

The loss-of-coolant accident (LOCA) in a nuclear reactor's recirculation system represents a significant threat to reactor safety and constitutes a critical area of nuclear safety research. A LOCA can have severe consequences, potentially leading to reactor core overheating. In such an event, coolant loss may cause fuel rod failure, resulting in radioactive material release into the containment structure. If the containment system is inadequate or fails, radioactive substances may escape into the environment, posing serious threats to public health and safety. Additionally, a LOCA could initiate cascading failures in safety systems, complicating reactor stabilization and emergency management, which may escalate incident severity. While many studies focus on the most severe scenario involving a ruptured recirculation pipe, most discussions concentrate on analyzing peak cladding temperatures, fuel rod failure, and oxidation levels relative to safety criteria. However, less attention is given to symptoms that may indicate the rupture's origin.

Hou et al. conducted safety analyses on the CNP 600 reactor using the RELAP5 program, investigating variations in key system parameters across different break sizes in recirculation loops during a LOCA. Their study revealed a

strong correlation between break size and coolant temperatures at the inlet and outlet of recirculation loops. Similar findings were graphically represented in data from JAERI's ROSA-III simulations. For LOCA calculations, the plant behavior and Peak Cladding Temperature (PCT) results predicted by the RELAP5 model were consistent with those reported by GEH.

Wang et al. simulated key severe accident phenomena including core uncover, cladding oxidation, cladding failure, debris relocation to the lower plenum, and vessel head failure. Their findings indicated that results from SR5, MAAP, and MELCOR were highly consistent in modeling critical accident phenomena, including steam generator dryout, core uncover, cladding oxidation, molten pool formation, debris relocation, and vessel head failure. Additionally, Yasuharu et al. demonstrated that both MAAP and RELAP5 produced consistent results in formulating incident management strategies, even in the absence of specific mitigation measures.

At the 9th European MELCOR Users Conference held in Spain in 2017, Mascari et al. reported that predictions of LOCA progression by ASTEC, MAAP, and MELCOR showed strong qualitative consistency, although some quantitative differences were noted. For example, when analyzing the time sequences of related phenomena, the maximum percentage difference in selected key safety parameters—referred to as the “figure of merit”—between ASTEC and MAAP/MELCOR was approximately 20%.

The “figure of merit,” also known as a characteristic value, is a performance metric used to evaluate equipment, system, or methodology effectiveness. The consistent predictions of transient phenomena by all three codes validate their reliability in modeling reactor accident progression. Furthermore, a 2013 technical report on MAAP code application to post-Fukushima accident analysis demonstrated that MAAP performed exceptionally well, with results closely aligned with those of the reference plant. This highlights that industry-standard accident analysis software can provide consistent trends for analyzed accidents.

Hwang's research further validated MAAP5 program accuracy in simulating the relationship between LOCA break sizes and temperature differences. The study found that different break sizes significantly affected temperature differences between inlet and outlet of recirculation pipelines and established a corresponding relationship between these temperature differences and pipeline break size. This discovery has promising practical applications, as operators can estimate break size by monitoring pipeline temperature differences without relying on additional external instruments. This improves accident assessment efficiency and provides crucial information for ensuring reactor safety during critical seconds immediately following an accident. However, the study also indicated that temperature difference fluctuations are influenced by the system recovery strategy implemented after rupture. Consequently, further research is necessary to comprehensively understand temperature difference behavior caused by pipeline ruptures, laying groundwork for optimizing diagnostic tools and recovery strategies.

The objective of this study is to develop a model that qualitatively describes temperature variation characteristics when pipe ruptures occur. The model is based on heat transfer, fluid dynamics, and energy balance principles, aiming to establish a qualitative framework to clarify this phenomenon and lay foundations for future in-depth research. By employing computer simulation programs, this study analyzes coolant pipe rupture effects on the recirculation cooling system and compares resulting trends with operator simulator data, seeking to further understand why the intact loop exhibits higher temperature than the broken loop.

METHOD

During a LOCA in a nuclear power plant, temperature differences appear between intact and broken sections of the recirculation loop. This study examines how pipe ruptures lead to these differences by analyzing trends, comparing results with BWR6/MARK-III simulator data, and conducting additional MAAP5 simulations.

[Figure 1: see original paper] Steam and recirculation water flow paths in a BWR, and the relevant location of the experiment.

Figure 1 illustrates coolant flow locations and directions during the LOCA experiment. Before any rupture, both recirculation loops have identical temperature and pressure. When rupture occurs in loop A, its state diverges from intact loop B.

[Figure 2: see original paper] Schematic diagram of the volume region between temperature and pressure at the broken pipe A and the intact pipe B.

Figure 2 separates the ruptured pipe A and intact pipe B, highlighting their distinct states, where the red line depicts recirculation cooling water flow direction following the LOCA accident. T_i represents the temperature of countercurrent flow from the lower plenum into the broken recirculation loop, which is related to decay heat time. T_0 is the original temperature in the recirculation loop, influenced by injected coolant T_i . T_2 is the bulk temperature after the break, which decreases over time. M_0 represents coolant mass in the control volume. The coolant mass flow rate of countercurrent flow from the lower plenum into the broken recirculation loop is also defined.

The dash line indicates the control volume. The rate of change of energy within the control volume equals the net rate of energy transfer into and out of the control volume. When the control volume has only one entrance and one exit, and under the assumption of no heat source and no work, and neglecting variations in kinetic and potential energy, we obtain the following equation:

$$\frac{dU}{dt} + \dot{m}(h_{out} - h_{in}) = 0$$

Where U is internal energy accumulated in the control volume, \dot{m} is mass flow rate into the control volume, M_0 is constant mass in the control volume, c_p represents specific heat capacity, $h = u + Pv$ is enthalpy per unit mass.

Based on Ferng' s and MAAP' s report, the mass flow rate can be expressed as:

$$\dot{m} = C_d A \sqrt{\frac{2(P - P_{rec})}{v_l}}$$

where \dot{m} is flow rate through the break, A is break area, C_d is discharge coefficient, P is upstream pressure at the break, v_l is specific volume of the fluid, $\eta = \max(P_{rec}/P, \eta_{crit})$, P_{rec} is downstream pressure at the break, $\eta_{crit} = \min(\eta_{crit}, P_{sat}/P)$, and $\eta_{crit} = 0.83 - (0.15/0.22)x$ for $x \leq 0.2$.

Solving for temperature variation using separation of variables with initial temperature at the control volume T_0 , where t is time from scram t_s to t :

$$\frac{dT}{dt} = -\frac{\dot{m}}{M_0}(T - T_i)$$

After integration and applying the initial condition when $t = t_s$, $T_2 = T_0$, then $t = t - t_s$:

$$T_2 - T_i = (T_0 - T_i)e^{-\frac{\dot{m}}{M_0}(t-t_s)}$$

Applying a Taylor series expansion for the exponential function:

$$e^x \simeq 1 + x + \frac{x^2}{2!} + \dots + \frac{x^n}{n!} + R_n$$

where $R_n = \frac{f^{(n+1)}(\xi)}{(n+1)!}(x - a)^{n+1}$.

Further simplification yields:

$$T_2 - T_0 = (T_0 - T_i) \left[1 - e^{-\frac{\dot{m}}{M_0}(t-t_s)} \right]$$

The temperature difference $T_2 - T_0$ represents coolant temperature change in the recirculation loop, which depends on break area A and pressure difference between upstream and downstream of the break. Assuming constant pressure difference, $T_2 - T_0$ is directly related to break area A . T_0 is coolant bulk temperature in the pipeline, and T_2 is coolant temperature after the break.

According to the derived equation, break cross-sectional area A is linked to temperature difference $T_2 - T_0$. Before the break, coolant temperature is T_0 , and after the break it changes to T_2 , transferring internal energy via enthalpy. If

there is no rupture, there is no temperature difference within the considered volume, leading to $(T_0 - T_i) = 0$. Consequently, $T_2 = T_0$, indicating no temperature difference between corresponding pipes in the two loops when no rupture occurs.

When considering decay heat Q after a scram, and with ECCS safety injection, counter-current coolant flow occurs through the lower plenum to the break location, leading to $T_i < T_0$. In the absence of safety injection water, coolant from the lower plenum is hotter than T_0 , meaning that $(T_0 - T_i)$ can be either negative or positive.

indicates that the signs (positive/negative) of each term depend on decay heat transferred from the lower plenum. The table provides detailed relationship assignments of positive and negative signs to various terms in the equation.

Due to the fact that decay heat Q continues to decrease with increasing shutdown time, T_i exhibits a decreasing trend, and overall coolant temperature T_0 inside the tube also drops. Consequently, the temperature difference between T_i and T_0 shows both positive and negative variations over time. When $T_i > T_0$, it indicates that temperature in the broken loop is higher than in the intact loop; conversely, when $T_i < T_0$, coolant temperature in the intact loop is higher than in the broken loop. Therefore, the presence or absence of water injection becomes the key factor affecting temperature difference, which will be discussed later.

In the Taylor series expansion, R_n represents the n -th order error term. Its value decreases as x gets closer to the center point, making the approximation more accurate, and as order n increases. MAAP5 simulates accident progression and impact analysis by considering factors such as pressure, fluid properties, and break geometry. The mass flow rate in the broken pipe is directly proportional to pressure difference between upstream and downstream. As break size increases, mass flow rate also increases, even if pressure difference remains constant, until reaching a critical flow state. At this point, outflow rate no longer increases, and mass flow rate reaches its critical value.

The temperature difference across the broken loop is directly proportional to pressure difference at the break. As break size increases, temperature difference between loops increases. Once mass flow rate reaches its critical value, temperature difference no longer increases and instead reaches a maximum across different break sizes. Based on this, the maximum temperature difference between the two loops can be determined.

VALIDATION AND EVALUATION

The scenario simulates a recirculation loop suction-side LOCA event occurring during normal operation. The break leads to rapid pressure drop, triggering a reactor scram. It is assumed that ECCS can successfully activate to makeup coolant. Temperature variations between broken and intact loops are observed

under this condition.

For this study, SBO and LOCA scenarios were selected as key indicators for simulation and qualitative assessment. To ensure accuracy, reliability, and validity of research conclusions, this study uses data from a simulator designed specifically for the reactor system. SBO is a severe accident scenario; however, the coolant loops remain intact. Comparing LOCA and SBO events, a standalone SBO event causes reactor scram while keeping piping intact. In contrast, a LOCA event not only triggers reactor scram but also involves loop break, leading to coolant loss. Through SBO and LOCA experiments, we can confirm that temperature difference is caused by rupture in the corresponding loop.

[Figure 3: see original paper] illustrates temperature data during an SBO accident simulated by the training simulator. Temperatures remain at 277°C for both loop A and loop B, consistent with the FSAR. The yellow line indicates temperature difference between the two recirculation loops. The horizontal trend shows no significant temperature difference, as there is no break in the loops. The green and blue lines represent temperatures of the intact and broken loops, respectively, which nearly overlap due to absence of rupture. According to the derived equation, since both Loop A and Loop B in the SBO scenario are intact and undamaged, we have $T_i = T_0$ and $T_2 = T_i = T_0$ in both loops. This result is consistent with the prediction of no break, no temperature difference.

To compare with the SBO scenario, an experiment involving LOCA was conducted, focusing on rupture in recirculation loop A. [Figure 4: see original paper] shows simulator data for the LOCA event. The rupture caused significant temperature difference between loops A and B. Before the break occurred at 14:36:14, the reactor was in normal operating conditions. After the LOCA, temperature difference between loops increased, exceeding 40°C and lasting for 150 seconds. While exact break size cannot be determined due to simulator limitations designed for training rather than experimental precision, the data clearly indicate that pipe rupture leads to significant temperature difference between intact and broken loops.

In Figure 4, the reactor scrambled at 14:36:21, and temperature difference between inlet recirculation loops began increasing until 14:38:24, lasting approximately 150 seconds. Comparison of Figures 3 and 4 confirms that observed temperature difference was due to pipe break rather than SBO. The temperature difference became apparent after reactor scram, as shown in simulator results. This temperature difference is a temporary condition, appearing from 14:36:21 to 14:38:24 with duration of about 2 minutes, after which it remains constant without temperature difference.

[Figure 5: see original paper] shows simulated temperature difference between inlets of loop A and loop B during LOCA, generated by the training simulator. Figures 3 through 5 illustrate outcomes of simulation conducted by the BWR6/MARK-III simulator. Although the simulator is a valuable tool for observing sequence of changes in reactor following parameter differences, it is

primarily designed for education and training of reactor operators rather than case studies; even though break sizes can be adjusted, the real break size cannot be known.

MAAP5 RESULTS

This section applied the MAAP5 program to simulate the SBO and LOCA experiments described above and compare results with those obtained from derived formula. According to the FSAR, the design pressure is 7.172×10^6 Pa (1040 psi). The pressure simulated by MAAP5 is 7.189×10^6 Pa (1042 psi), while the simulator shows 7.215×10^6 Pa (1045.7 psi). The temperature at the recirculation loops is 551 K, and according to the FSAR, it is 549 K when simulated by MAAP5 and 550 K by the simulator. This indicates that simulation errors for both temperatures and pressures in MAAP5 and simulator compared to the FSAR are less than 0.3%.

compares temperature and pressure values in FSAR, simulator, and MAAP5.

Figures 6 and 7 demonstrate that MAAP5 simulations of SBO and LOCA scenarios align with trends observed in the training simulator. According to the derived equation, temperature in the intact loop is higher than in the broken loop. Since coolant flow through the rupture reaches a critical value at certain pressure, temperature difference is expected to have a maximum for specific break size, as previously described. Thus, in MAAP5 simulation results, maximum temperature difference was identified for each break size, validating consistency between MAAP5 program and training simulator for both SBO and LOCA conditions.

[Figure 6: see original paper] demonstrates MAAP5 simulation of SBO in a BWR6/MARK-III. [Figure 7: see original paper] presents LOCA results from MAAP5 simulations, consistent with trends shown in Figure 4 from the training simulator. Since the simulator is based on data retrieved from resistance temperature detectors (RTD) from the power plant, and considering each sensor has detection limits, all data below 0.4°C are considered noise in the simulation, as this falls within RTD detection limits.

Figure 7 demonstrates MAAP5 simulation of LOCA in a BWR6/MARK-III. After reactor scram due to break in recirculation loop causing coolant loss, temperature difference is evident between intact and broken loops. This LOCA phenomenon is clearly shown by both MAAP5 simulations and training simulator in Figures 5 and 7, displaying the same trend. The consistency between MAAP5 simulations and training simulator validates reactor characteristics observed in both tools. According to EPRI (2013), the MAAP formula for BWR reactors in LOCA accident transients from 7 minutes to 40 hours shows good consistency with responses of various reference power plants. Ferng demonstrated that the MAAP program's RCS model primarily simulates thermal-hydraulic response, thermodynamic properties of cooling water, and transient rate of change in system parameters.

The results demonstrate that both simulator and MAAP5 produced consistent response patterns. It has been confirmed through SBO and LOCA experiments that temperature difference is caused by rupture in the corresponding loop.

DISCUSSION

Previous cross-validation between SBO and LOCA simulators and MAAP5 has shown that break is the primary factor responsible for temperature difference. This section compares these results with those from a simplified model, and analysis confirms the relationship between rupture mechanism and temperature difference.

Following instantaneous pipeline rupture, the system remains initially unchanged while temperature difference between loops gradually increases. During a LOCA, the recirculation pump stops, causing reverse flow in the broken loop while the intact loop continues briefly due to coolant inertia. Backflow through the jet pump may mix with hotter core coolant ($T_i > T_0$) or ECCS coolant ($T_i < T_0$). The reverse flow carries hot coolant from the core through the lower plenum and jet pump, exiting via the break and influencing overall temperature difference. The derived equation shows this difference depends on break size and follows an exponential or first-order polynomial function, requiring experimental validation.

Case 1: $T_i > T_0$

This scenario occurs after reactor LOCA scram where all emergency cooling systems remain inactive, leaving only decay heat from core fuel to heat gradually decreasing reactor water, as [Figure 8: see original paper] demonstrates. The reverse flow directs hotter coolant from reactor core through lower plenum and jet pump, exiting through the break. [Figure 9: see original paper] clearly shows that when reactor undergoes scram due to LOCA caused by breakages of different sizes and no emergency injection is provided, the condition $T_i > T_0$ occurs. According to equation prediction, temperature of broken loop should be higher than intact loop as $T_i > T_2 > T_0$. Results predicted by this model are consistent with those simulated by MAAP5.

Case 2: $T_i < T_0$

Due to reactor scram caused by rupture in recirculation loop, high core pressure forces large amount of coolant to discharge in reverse from the break. At this time, all designed water injection systems activate according to their intended functions. Injection water is sourced from facilities such as condensate storage tank (CST) or suppression pool, with temperature typically set at 60°C, far lower than reactor normal operating temperature of 277°C. Therefore, as long as any injection system operates normally, condition $T_i < T_0$ is maintained, with heat transfer relationship $T_i < T_2 < T_0$. This analysis reveals that counter-current flow temperature in broken recirculation loop affects its internal water temperature, leading to temperature difference between loops.

[Figure 10: see original paper] shows LOCA-induced scram with all safety in-

jection systems functioning as originally designed. Previous study confirmed that temperature of counter-current flow coolant causes different temperature difference patterns at the break. Furthermore, based on the derived equation, temperature difference is related to break area, as shown in Figures 9 and 10, and can be expressed as:

$$T_2 - T_0 \propto (A \cdot \Delta P)$$

Herein, the assumption of constant pressure difference may not be entirely accurate. However, according to break definitions categorized into large, medium, and small breaks, typically a break area equivalent to 10% of main coolant pipe cross-sectional area serves as threshold between large and medium breaks, while 2% of pipe cross-sectional area serves as boundary between medium and small breaks. Therefore, for a 20-inch pipe, break size of 300 cm² falls into large break category. In Figure 10, curves in different colors represent pressures for various break sizes ranging from 6 cm² to 600 cm². When pipeline breaks and internal pressure is 6.576 × 10⁶ Pa (957 psi), this represents reduction from 7.189 × 10⁶ Pa (1042 psi) of 8.3% for 300 cm² break. Impact of pressure drop caused by break on system is less than 10% within 300 seconds. If break is even smaller, pressure difference decreases further, with change of only about 5%. Therefore, relationship can be approximated as proportional to break size within certain range. Pressure drop in reactor cooling system after break occurs is a function of time, as shown in [Figure 11: see original paper], which displays pressure curves in different colors representing breaks of various sizes from 6 cm² to 600 cm².

For each different break size, there should be corresponding maximum break flow rate and maximum pressure drop. Ferng' s report also shows that mass flow rate of break is proportional to pressure difference between upstream and downstream. When pressure difference reaches certain level, break flow rate reaches critical value and no longer continues to increase. Therefore, as break size increases, mass flow rate also increases, even if pressure difference remains constant, eventually reaching critical flow state. Thus, maximum temperature difference corresponds to different break sizes. In absence of water injection, reactor core will be exposed within few minutes to several tens of minutes depending on break size.

The simplified model can reasonably predict relationship between break and temperature difference, applying to both water injection and non-water injection scenarios. Additionally, it can quickly assess break within short period, as demonstrated by [Figure 12: see original paper] and [Figure 13: see original paper].

[Figure 12: see original paper] shows break size spectrum at 50 seconds after reactor scram. Primary observed phenomenon is that temperature in intact loop is higher than in broken loop. The figure shows that without RCIC and ECCS backup, coolant temperature in broken loop is higher than in intact loop,

primarily due to high-temperature water from reactor core flowing through lower plenum and recirculation loop to break location. No RCIC and ECCS is only in extremely rare cases where water injection is entirely unavailable or during transient moment of break might broken loop temperature exceed that of intact loop. In the equation, when $T_i > T_2 > T_0$, both left-hand side and right-hand side are positive, indicating temperature in broken loop is higher than in intact loop. Probability of this situation occurring is very low.

Under normal operating conditions, break triggers emergency reactor shutdown followed by sequential RCIC and ECCS water injection. [Figure 13: see original paper] shows temperature deviation between broken and intact loops. When $T_i < T_2 < T_0$, both left-hand side and right-hand side are negative, indicating temperature in intact loop is higher than in broken loop. Normally, as long as reactor backup cooling system operates properly, it can effectively cool reactor core.

In Excel, the R^2 value of a linear trend line is a statistical measure used to evaluate how well fitted model matches actual data. Therefore, R^2 values of fitting function are also posted in Figures 12 and 13. Data and functions of fitted curves show correlation of over 90%, indicating that shortly after reactor scram, the derived equation still aligns with characteristics of this open system. R^2 ranges from 0 to 1, where $R^2 = 1$ indicates perfect fit (all data points fall exactly on trend line, meaning model explains all data variation) and $R^2 = 0$ indicates no fit (trend line explains none of data variation). In Figures 11 through 13, trend lines and their R^2 values corresponding to sampling times are clearly indicated, showing that as sampling time increases, R^2 value of trend lines decreases.

Distribution of blue dotted points is approximately fitted by red dashed line, with corresponding temperature differences also included. Results show that MAAP5 simulation aligns with constructed model, indicating that when safety injection system is activated, intact loop temperature is higher than broken loop temperature. This provides theoretical foundation for further research and application. Temperature difference of broken pipe exhibits linear relationship with break size, as calculated by fitting equation posted in figures. According to Figure 12 linear fitting curve of MAAP5 data, which is approximately 95% consistent with properties of straight line with zero intercept, this verifies rationality of relevant assumptions and provides important basis for understanding thermal response characteristics of system. However, temperature difference of broken loop and broken flow rate equations show that smaller downstream pressure results in greater broken flow rate, meaning larger break size. Both expressions demonstrate relationship to fracture break size and pressure difference.

CONCLUSION

This study uses MAAP5 program to analyze temperature and pressure variations in reactor cooling system of BWR6/MARK-III nuclear power plant during

LOCA and SBO events and their effects.

1. This study confirms that temperature difference in recirculation loop is caused by emergency injection water flowing in counter-current flow through the break. Given presence of critical flow rate at break, selecting maximum temperature difference within sampling period is reasonable approach.
2. Under normal operating conditions, break leads to reactor scram followed by sequential ECCS water injection. This results in primary observation that intact loop maintains higher temperature than broken loop. However, in rare cases where water injection fails or during initial transient phase, broken loop may temporarily exhibit higher temperature.
3. MAAP5 simulation results align with predictions of derived equation and numerical simulations, confirming that temperature difference between loops is influenced by break size.
4. Based on simple estimation, magnitude of temperature difference can indeed be linked to break size.

It should be noted that this analysis uses BWR6/MARK-III as example, but findings are not limited to this model. MAAP5 simulation data aligns with these findings, confirming model robustness and suggesting further applications for system response analysis and simulation tool development. Future work can further explore relationship between break size and temperature difference to enhance safety and reliability of reactor operations, and further calibrate MAAP5 program with real reactor parameters to enhance accuracy in modeling pipeline rupture scenarios.

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Note: Figure translations are in progress. See original paper for figures.

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