Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 18,2023

PX : Asymmetric two-step thermosiphon for the containment cooling of SMR

1. 개 요
2. Multi-step thermosiphon
3. Two-step Thermosiphon
4. PX 이론 및 검증 해석
5. 개념의 SMR 적용
6. 요 약

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2023. 5. 18

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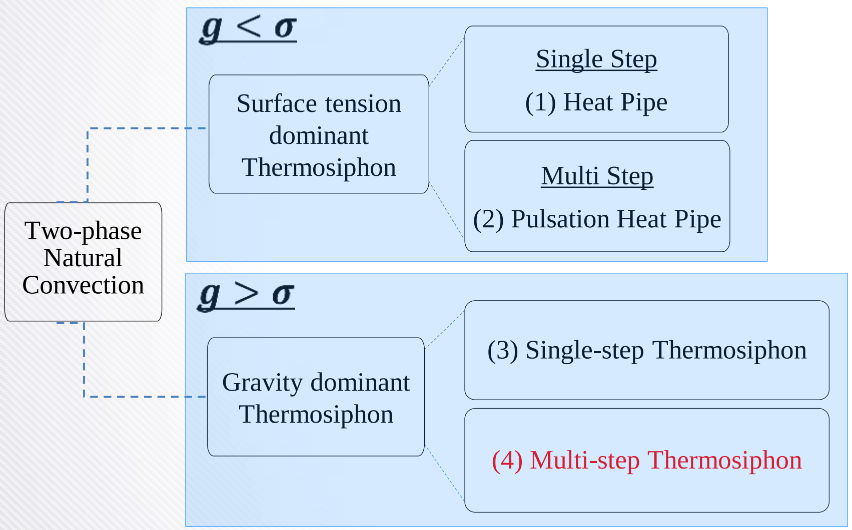
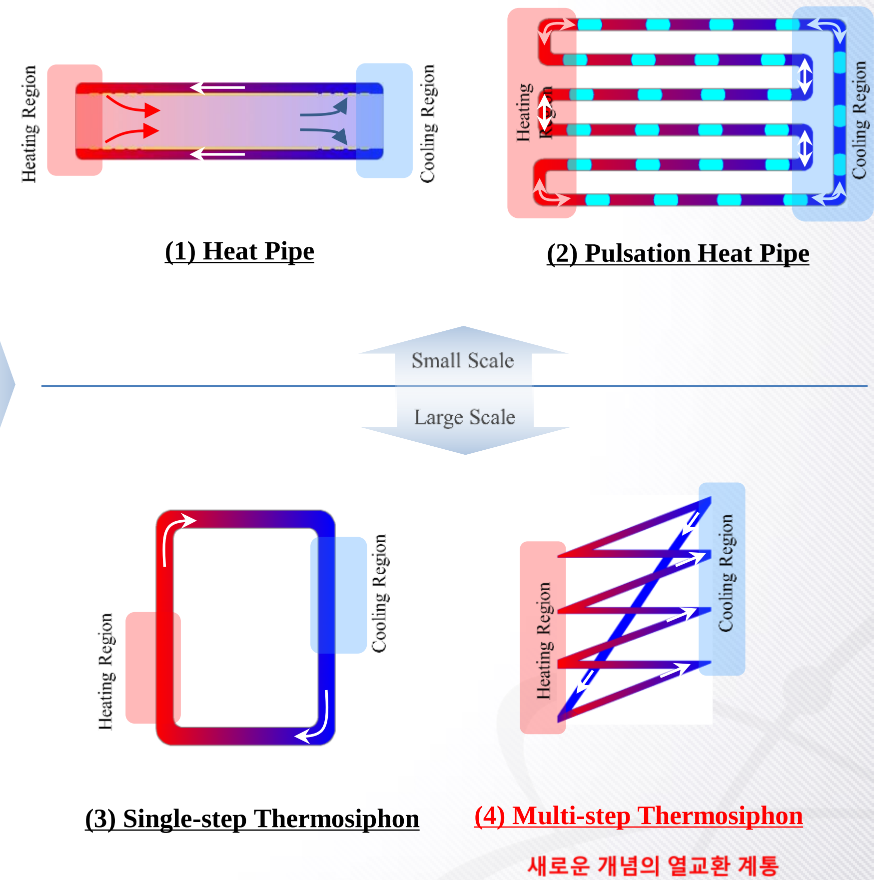
개 요

상변화에 의한 자연순환 열전달 방식 분류



자연순환 방법에 따른 열교환기 적용사례



[1] P. Dunn and D. A. Reay, "Heat pipes." Pergramon press, 1978.
[2] Amir Faghri, "Heat pipe science and technology." Taylor & Francis, 1995.
[3] B.Y. Tong, T.N. Wong and K.T. Ooi, "Closed-loop pulsating heat pipe," *Applied Thermal Engineering*, 21, pp. 1845-1862, 2001

02 Single-step & Multi-step Thermosiphon

Single & Multi Step Thermosiphon 열전달 성능 비교

❖ 열전달 해석을 위해 각 열원과 열침원에 대하여 Discrete 분포

1) 각각 n 개의 열원과 열침원 set 모의
2) Thermosiphon은 포화상태 이하 유지
3) 동일한 압력조건

지배 방정식을 각 Thermosiphon에 적용

M. Balance Eqn. : $f\frac{\rho}{2}v^2 = \oint \Delta p$

E. Balance Eqn. : $Q = \dot{m}\Delta h$

O-loop : Single-step Thermosiphon

$$\oint \Delta p_O = g[(\rho_O^0+\rho_O^1+\ldots\rho_O^{n-1}) - (\rho_O^1+\rho_O^2+\cdots\rho_O^n)]\Delta y = g(\rho_o^0-\rho_o^n)\Delta y$$

$$\sum Q_O^i = \dot{m}_O[\Delta x_O^1 h_{fg,O} + \Delta x_O^2 h_{fg,O} + \cdots \Delta x_O^n h_{fg,O}] = \dot{m}_O \sum \Delta x_O^i\, h_{fg,O}$$

X-loop : Multi-step Thermosiphon

$$\oint \Delta p_X = g[(\rho_X^0-\rho_X^1) + (\rho_X^0-\rho_X^1) + \cdots (\rho_X^0-\rho_X^1)]\Delta y = ng(\rho_X^0-\rho_X^1)\Delta y$$

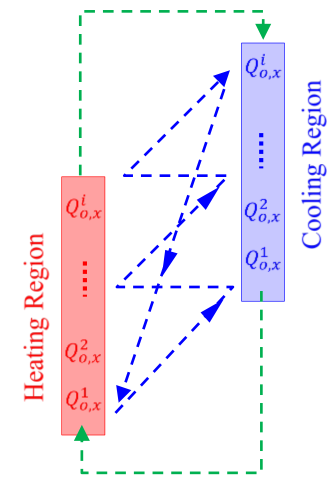
$$\sum Q_X^i = \dot{m}_X[\Delta x_X^1 h_{fg,X} + \Delta x_O^2 h_{fg,X} + \cdots \Delta x_O^n h_{fg,X}] = \dot{m}_X \sum \Delta x_X^i\, h_{fg,X}$$

Comparison of the circulation mass flow & heat transfer rate

	Single-step thermosiphon	Multi-step thermosiphon	Ratio
Flow rate ($\dot{m}$)	$\dot{m}_O = \left(\frac{2\bar{\rho}A^2}{f} g(\rho_O^0-\rho_O^n)\Delta y\right)_O^{1/2}$	$\dot{m}_X = \left(\frac{2\bar{\rho}A^2}{f} ng(\rho_X^0-\rho_X^1)\Delta y\right)_X^{1/2}$	$\frac{\dot{m}_X}{\dot{m}_O} \approx n$
Total heat Transfer rate ($\sum Q^i$)	$\dot{m}_O h_{fg,O}$	n $\dot{m}_X h_{fg,X}$	$\frac{\sum Q_X^i}{\sum Q_O^i} \approx n^2$

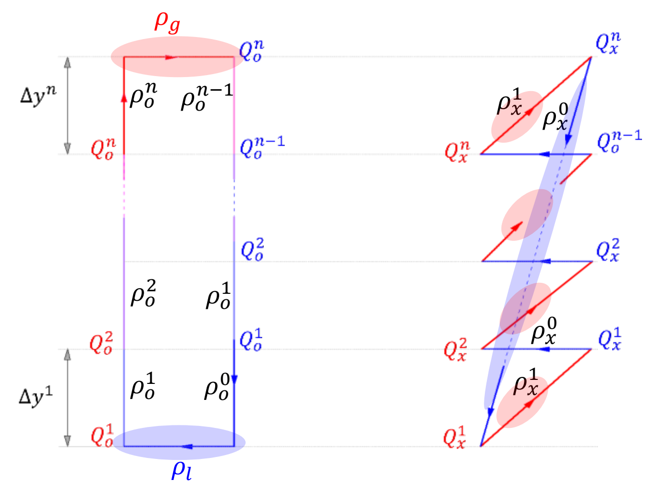
$if\ \rho_O^n, \rho_x^1 = \rho_g\ and\ \rho_O^0, \rho_x^0 = \rho_l$

Heat transfer & Circulation Mechanisms



O-loop : **Single-step** thermosiphon

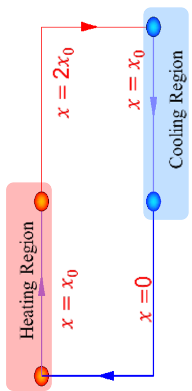
X-loop : **Multi-step** thermosiphon



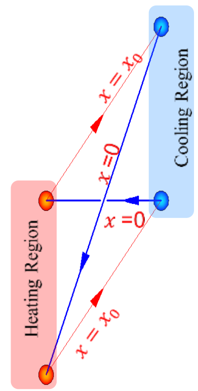
03 O-loop & X-loop 열교환 능력 비교

n=2 경우

- 한번 가열에 증기 건도가 동일한 x_0 만큼 증가하는 조건에서 비교 (동일한 조건의 가열 과 냉각)
- Homogeneous & Equilibrium Model(HEM) 조건에서 전산해석 수행



O-Loop :
Single step thermosiphon



X-Loop :
Two-step thermosiphon

전산해석 방법

Mass : $M = Consant$

Momentum : $\dot{m} = \left(\frac{2\bar{\rho}A^2}{f} g(\rho^0 - \rho^n)\Delta y\right)^{1/2}$

Energy : $Q^i = \dot{m} \sum \Delta x^i h_{fg}$

1. Set the total mass, heat transfer rate and pressure
2. Predict Mass flow
3. Solve Energy Equation
4. Cal. Quality from steam table
5. Cal. Density from steam table
6. Correct on the mass flow
7. Conform convergence of mass flow

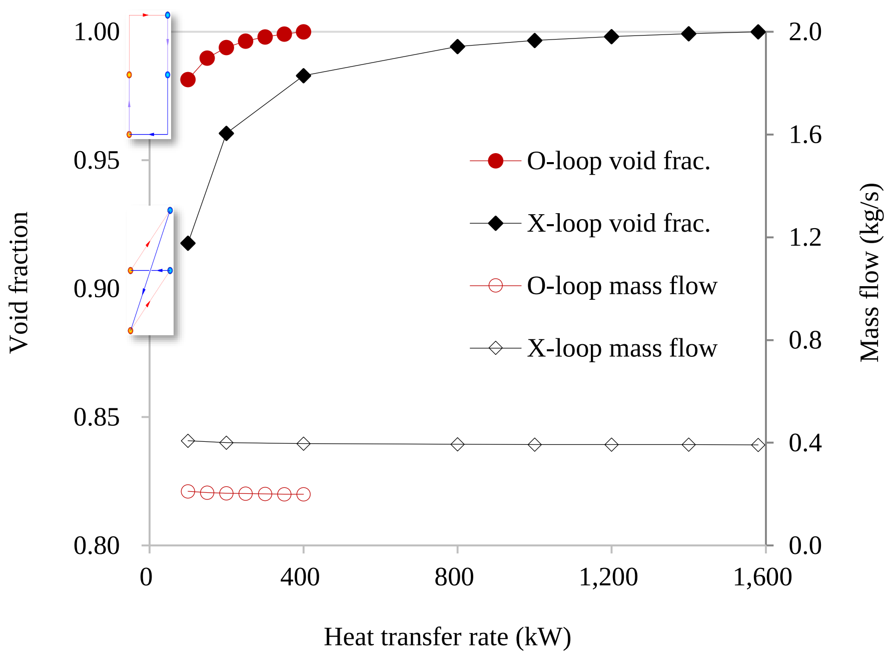
Loop pressure : 1 MPa		Total mass (kg)	Mass flow (kg/s)	Total energy (J)	Top region quality	Specific volume (m^3/kg)
Heat transfer rate **200 kW (100 +100)**	**O-loop**	1215.023	0.199	9.848E+08	0.500	0.006
	X-loop	1220.094	0.198	9.523E+08	0.250	0.003
	Ratio	1.004	0.998	0.967	0.501	0.498
Heat transfer rate **380 kW (190+190)**	**O-loop**	1189.466	0.200	9.656E+08	0.995	0.006
	X-loop	1190.054	0.197	9.297E+08	0.504	0.003
	Ratio	1.000	0.987	0.963	0.507	0.500

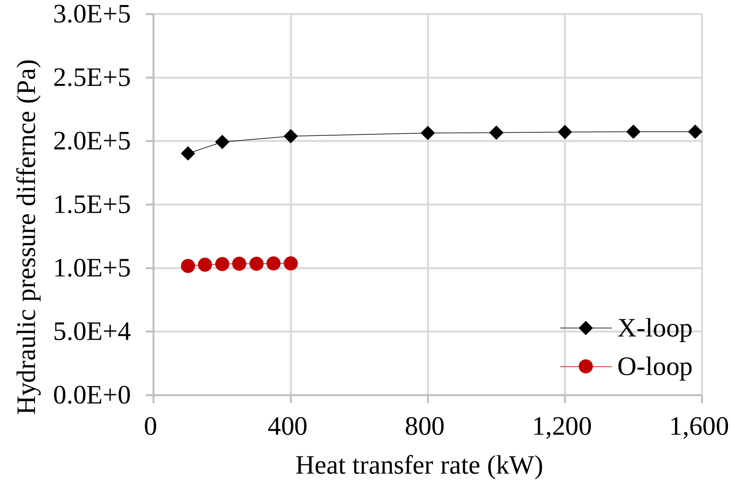
"동일 열수력조건에서 Two-step 경우 Single-step에 비하여 열전달 능력은 2배, 체적은 1/2"

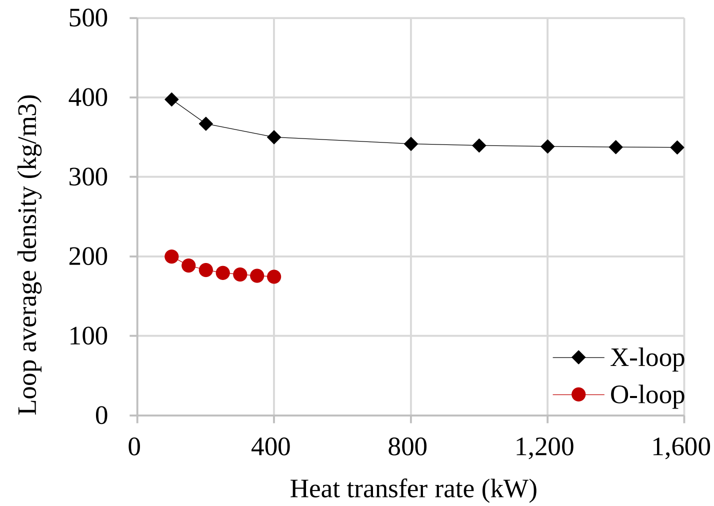
03 O-loop & X-loop 열전달 특성 비교

n=2 , volume ratio : 1 (X-loop / O-loop)

1. The ratio of circulation flow rate ≈ 2.0, $\frac{\dot{m}_X}{\dot{m}_O} \approx n$
2. The ratio of max. heat transfer rate ≈ 4.0, $\frac{\sum Q_X^i}{\sum Q_O^i} \approx n^2$







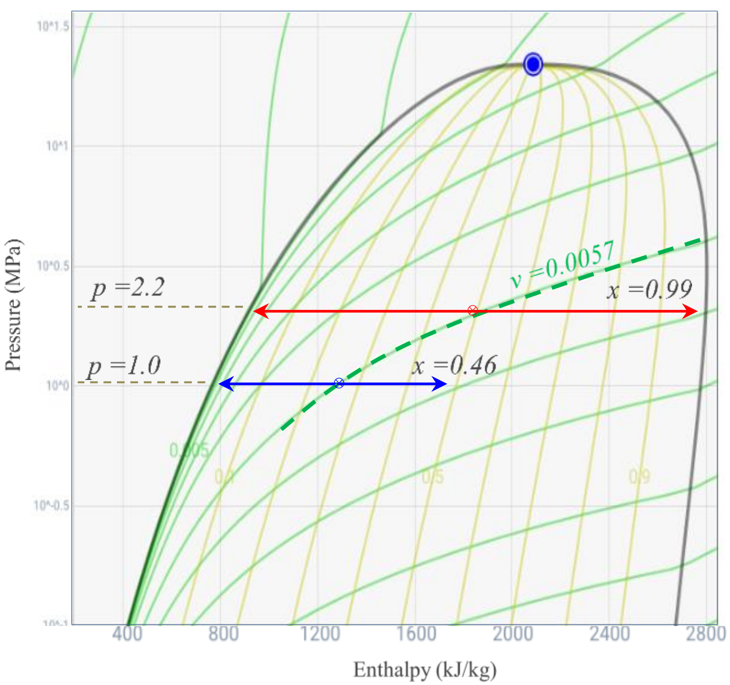
03 O-loop & X-loop 열전달 특성 비교

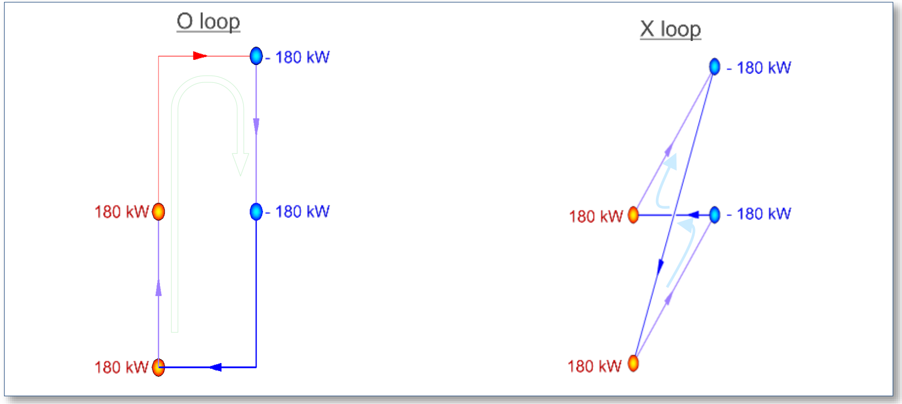
동일한 열수력 조건에서
압력 비교 해석:

1. Volume
2. Heat transfer rate
3. Total mass
4. Circulation mass flow

1. Total Volume : 7 m^3 (H × W : 24 m × 4 m)
2. Heat Transfer Rate : 380 kW
3. Total Mass : 1225 kg
4. Specific Volume : 0.0057

Steam p-h diagram





The ratios for X-loop / O-loop

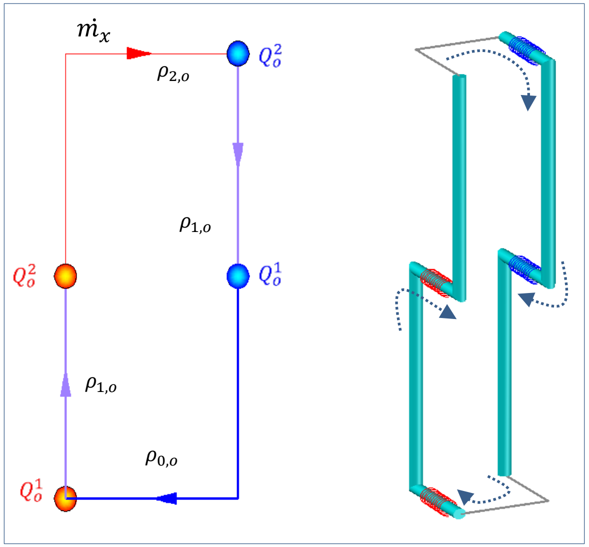
1. Max. quality : 0.46/0.99
2. Pressure : 1.0 / 2.2 (MPa)

04 O-loop & X-loop 열수력 해석

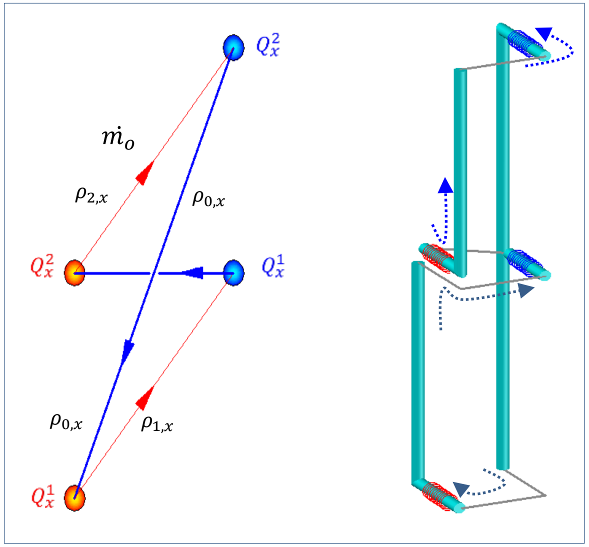
- **Realistic Code Simulation (MARS code Ver. 1.5)**

1. 초기조건 : 1.0 MPa, 포화상태 물
2. 경계조건 : 각 열원(열침원) 출력은 150 kW (Total 300kW)

O Loop



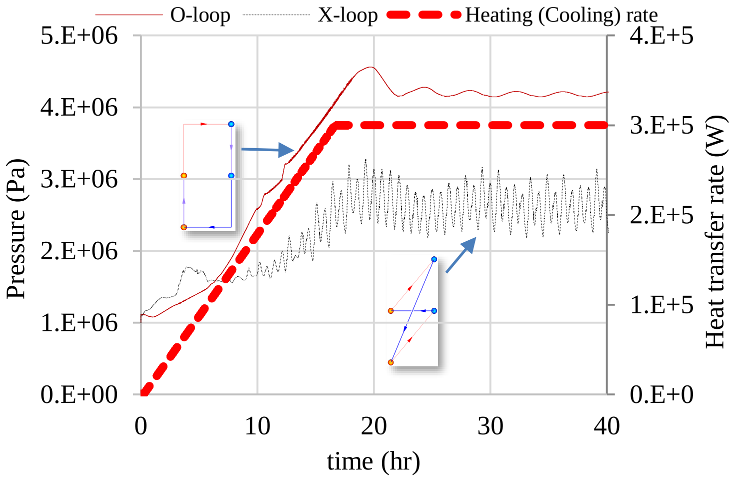
X Loop

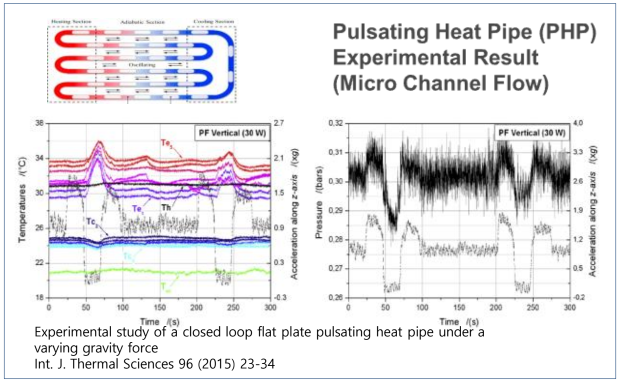


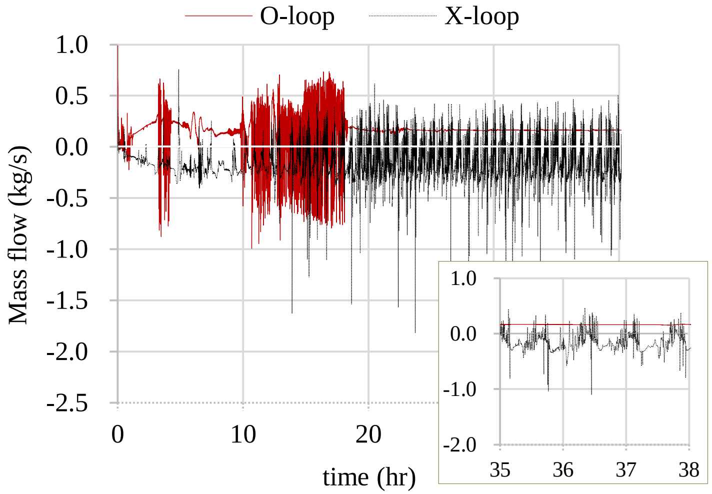
04 O-loop & X-loop 해석 결과 비교

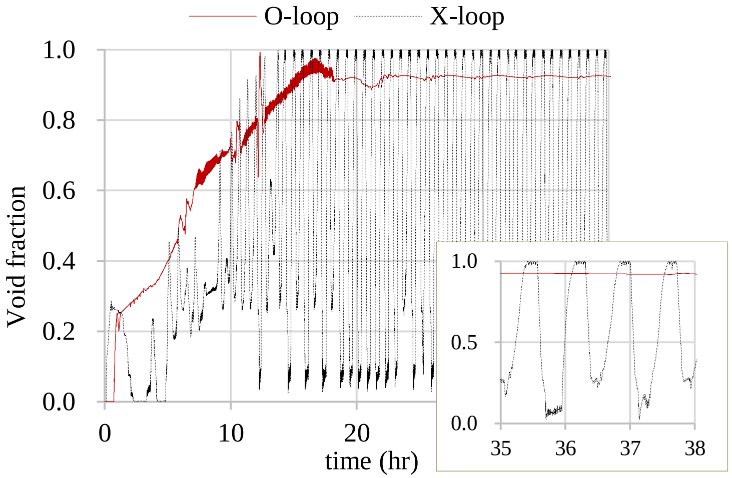
- **Realistic Simulation Results**

- 동일 초기 및 경계 조건에서 서서히 가열/냉각 (Total 300kW)



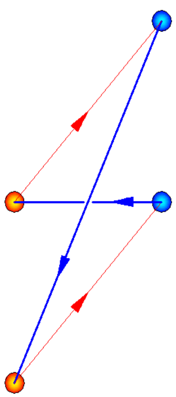


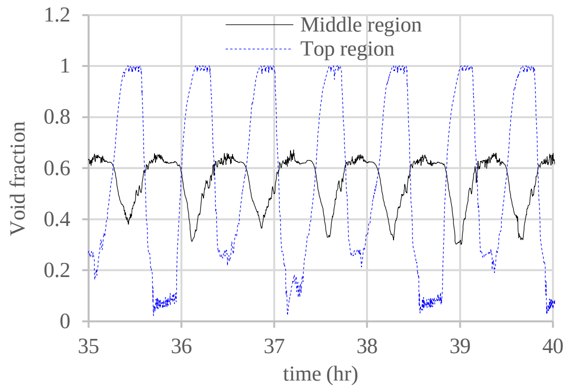


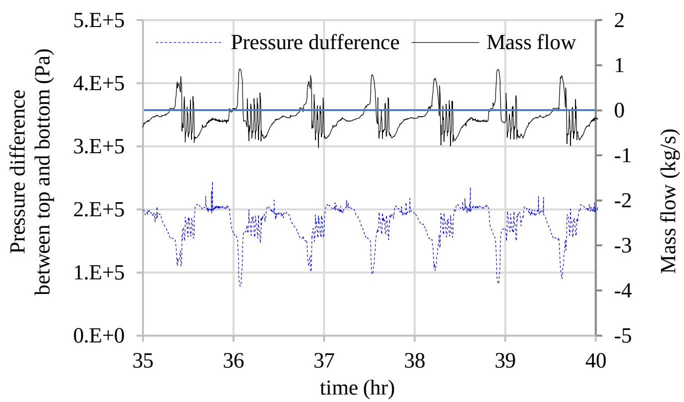


- **Pressure Ratio (X-Loop / O-loop) : 0.6**
- **X-loop : Pulsating flow as PHP (backward / forward)**

04 X-loop Instability 분석







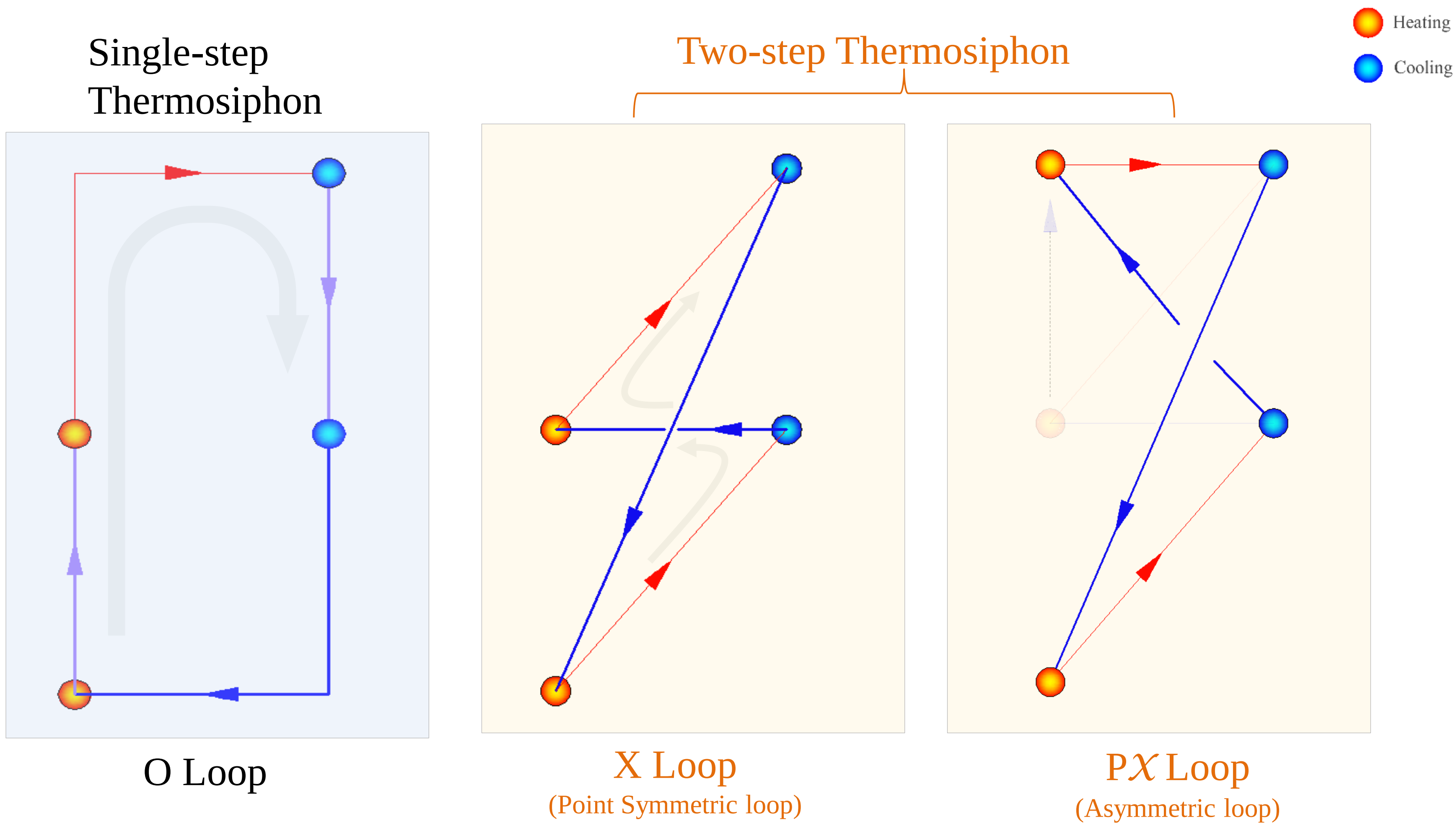
Classification of flow instability.

Class	Type	Mechanism	Characteristics
1. Static instabilities 1.1. Fundamental (or pure) static instabilities	1. Flow excursion or Ledinegg instability	$\frac{\partial \Delta p}{\partial G}\Big\|_{int} \leqslant \frac{\partial \Delta p}{\partial G}\Big\|_{ext}$	Flow undergoes sudden, large amplitude excursion to a new, stable operating condition
	2. Boiling crisis	Ineffective removal of heat from heated surface	Wall temperature excursion and flow oscillation
1.2. Fundamental relaxation instability	1. Flow pattern transition instability	Bubbly flow has less void but higher ΔP than that of annular flow	Cyclic flow pattern transitions and flow rate variations
1.3. Compound relaxation instability	1. Bumping, geysering, or chugging	Periodic adjustment of metastable condition, usually due to lack of nucleation sites	Period process of super-heat and violent evaporation with possible expulsion and refilling
2. Dynamic instabilities 2.1. Fundamental (or pure) dynamic instabilities	1. Acoustic oscillations	Resonance of pressure waves	High frequencies (10–100 Hz) related to time required for pressure wave propagation in system
	2. Density wave oscillations	Delay and feedback effects in relationship between flow rate, density, and pressure drop	Low frequencies (1 Hz) related to transit time of a continuity wave
2.2. Compound dynamic instabilities	1. Thermal oscillations	Interaction of variable heat transfer coefficient with flow dynamics	Occurs in film boiling
	2. BWR instability	Interaction of void reactivity coupling with flow dynamics and heat transfer	Strong only for a small fuel time constant and under low pressures
	3. Parallel channel instability	Interaction among small number of parallel channels	Various modes of flow redistribution
2.3. Compound dynamic instability as secondary phenomena	1. Pressure drop oscillations	Flow excursion initiates dynamic interaction between channel and compressible volume	Very low frequency periodic process (0.1 Hz)

J.A. Boure, A.E.Bergles and L.S.Tong, Review of two-phase flow instability, Nuclear Engineering and Design 25 (1973) 165-192

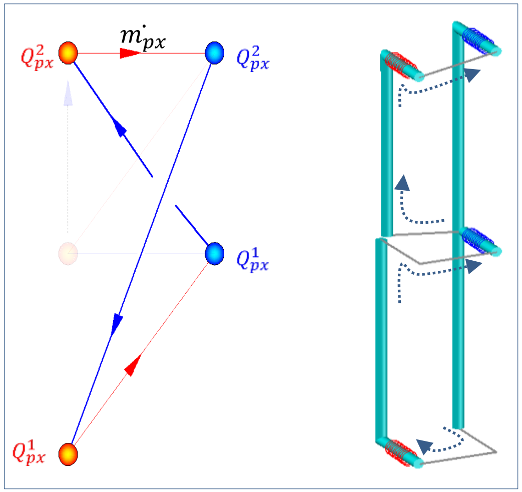
05 PX : Asymmetric Two-step Thermosiphon

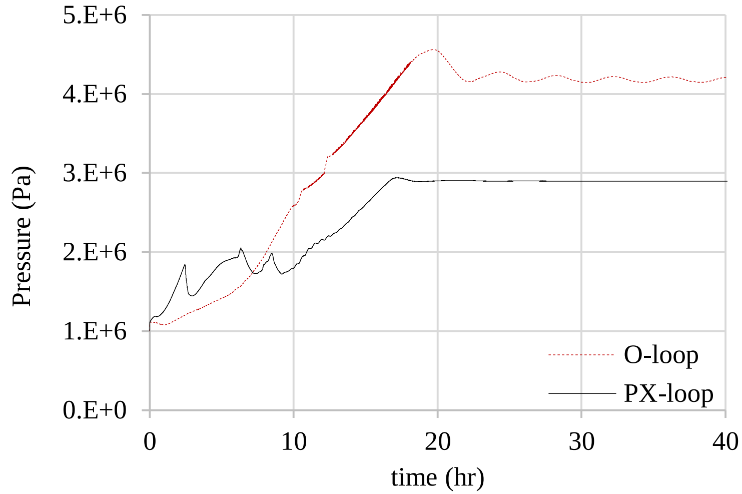
1. X-loop에서의 심한 Pulsation 현상의 주된 원인은 중앙으로 부터의 Point Symmetric 한 기하학적 특성으로 예상됨
2. Pulsation 현상 제거을 위한 방법으로 asymmetric loop 구조 제안

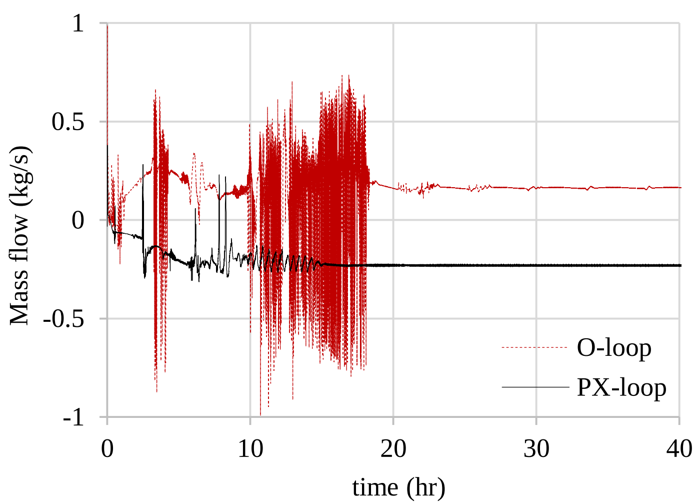


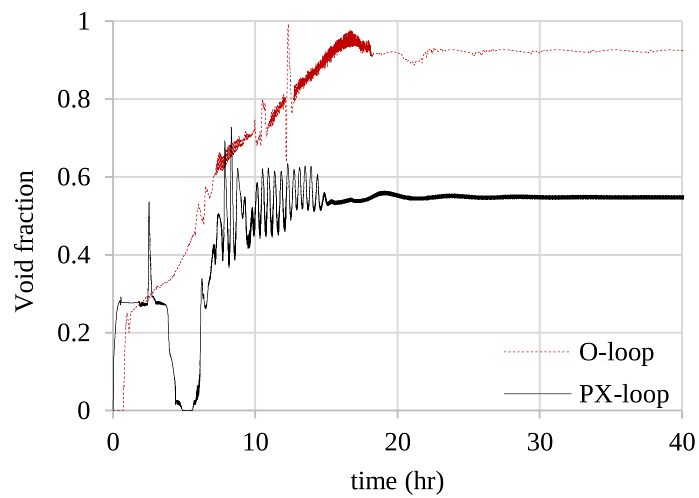
05 O-loop & PX-loop 해석 결과 비교

PX Loop



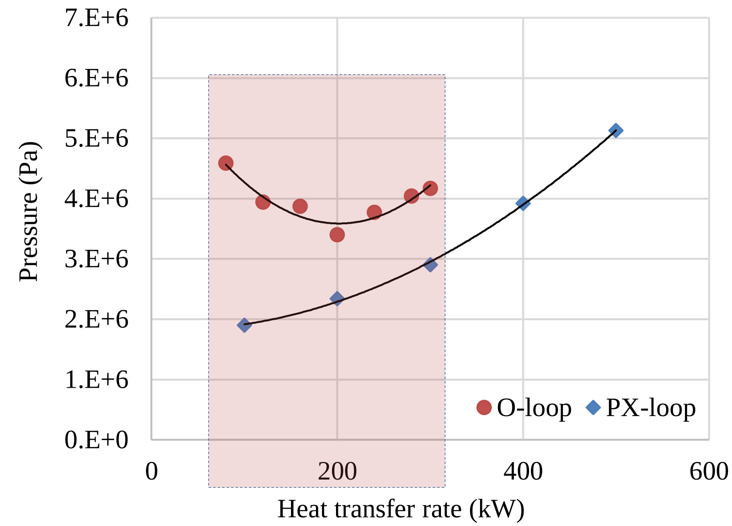


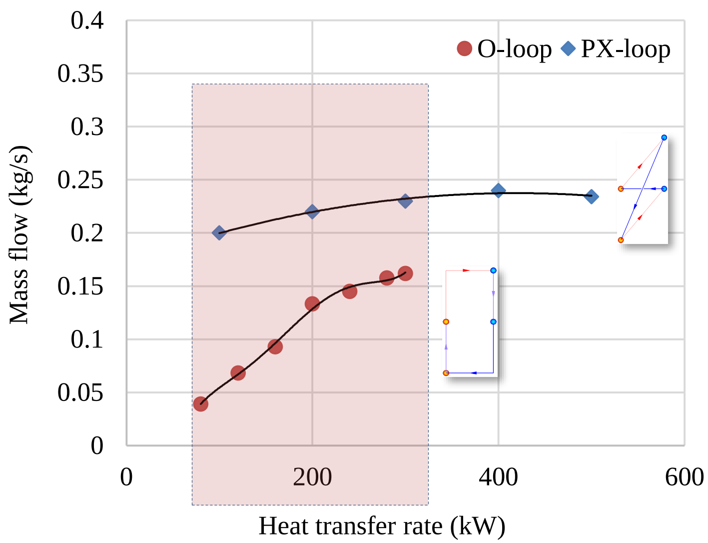


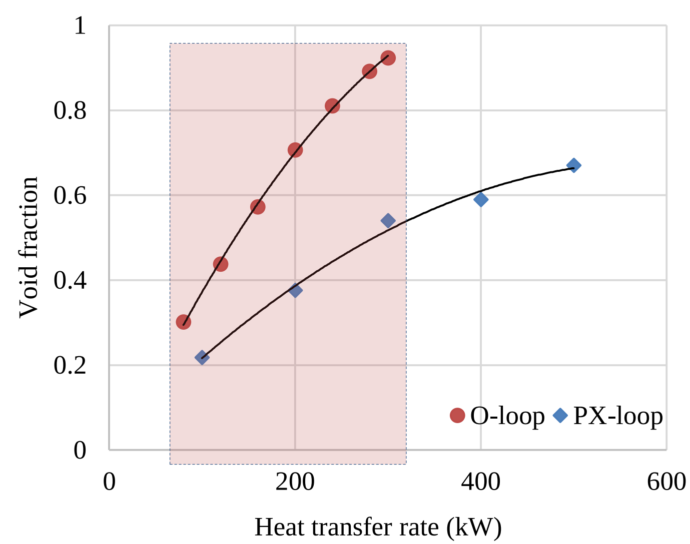


05 O-loop / PX-loop 자연순환 해석 종합

- **Realistic Simulation Results**
  - **Heat transfer rate range : 75kW ~ 500 kW**
  - **O-loop max. heat transfer rate : 380 kW**
  - **PX-loop max. heat transfer rate : > 500 kW**
    - ✓ 500 kW이상에서 코드 해석 어려움 발생

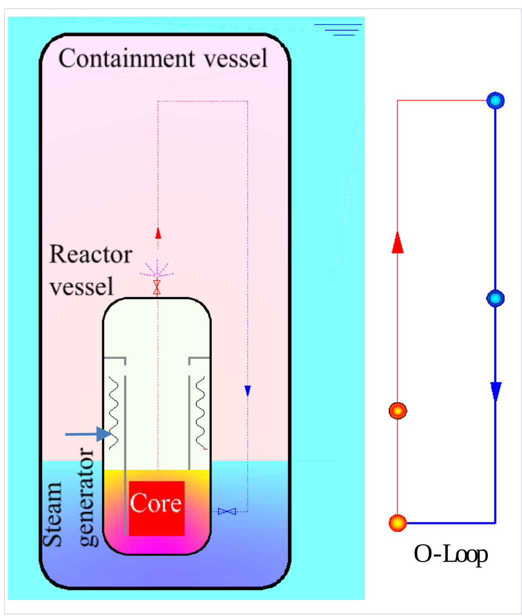


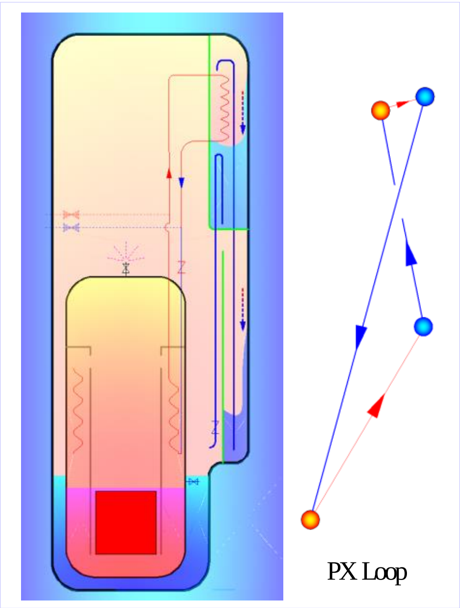




05 피동무한냉각(PX)의 SMR 격납용기 적용

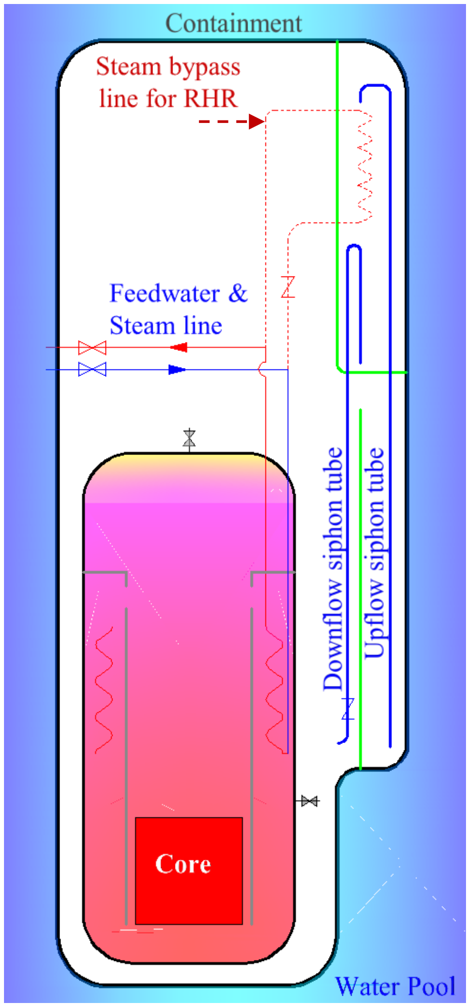
- PX : Asymmetric Two-steps Thermosiphon
- Lower Steam Pressure & Temperature
- Internal RHRS



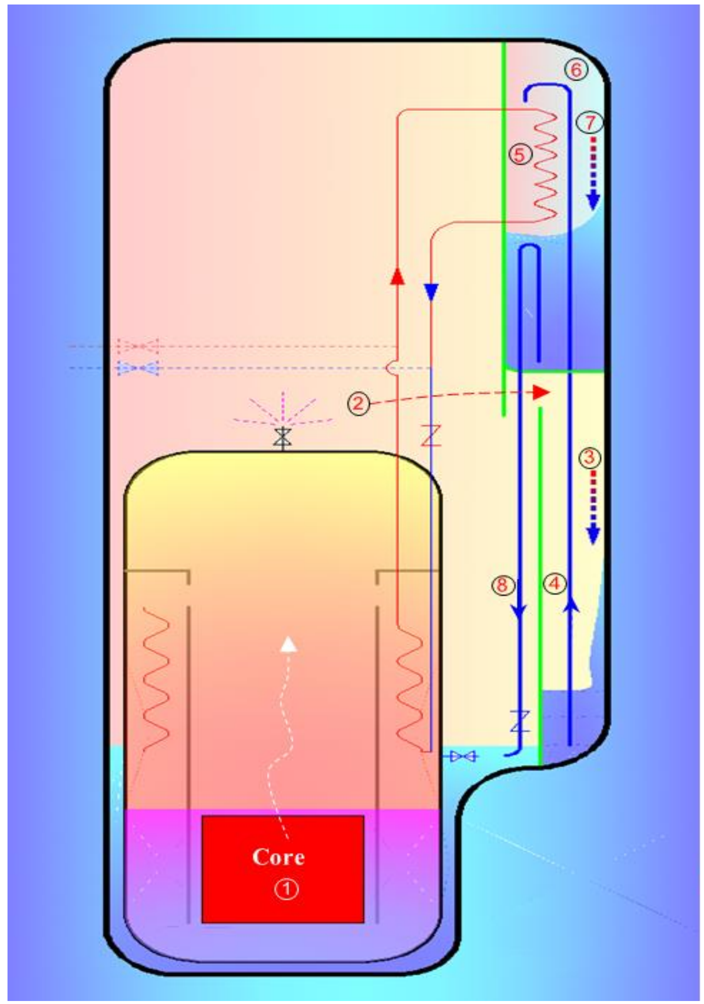


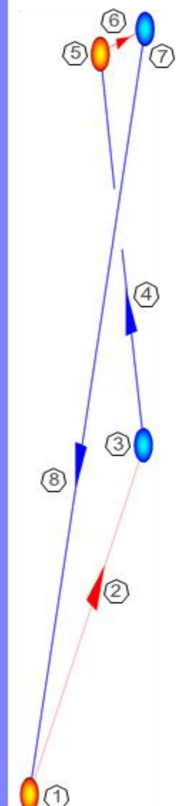
05 SMR 사고시 격납용기 냉각 적용

PX 적용 격납용기 구조



PX 냉각 열수력 거동





Local Thermal-hydraulic Phenomena

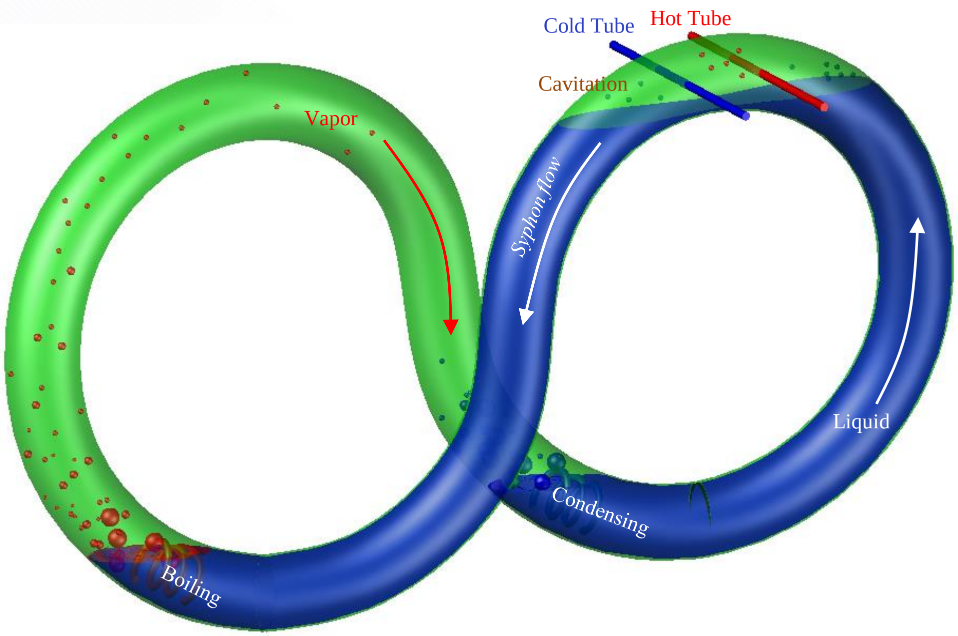
1. Boiling (Reactor wall or core)
2. Steam Expansion (Outflow to containment wall)
3. Wall Condensation (Containment lower wall)
4. Siphon Flow (Siphon Upflow)
5. Boiling (Tube shell side)
6. Steam Expansion (Tube to containment wall)
7. Wall Condensation (Containment upper wall)
8. Return Flow (Siphon Downflow)

요 약

1. **새로운 개념의 자연순환 열전달 소개 : Multi-step thermosiphon**
   - Two-step thermosiphon (X-loop, PX-loop) 이론 연구
   - 전산해석 검증 및 기존방식과 (O-loop) 비교 분석

2. **PX-loop :**
   - SMR 격납용기 냉각에 적합
   - 동일 체적, 최대 열전달 성능 비 (PX-loop/O-loop) ≈ 2 ~ 4
   - 동일 열전달조건의 체적비 & 압력비 (PX-loop/O-loop) ≈ 1/2 ~ 1/4

참고 자료



PX : Passive Infinite Cooling
(Asymmetric Two-step Thermosiphon)

PX 연구 목표

궁극적인 원자로 안전성 구축

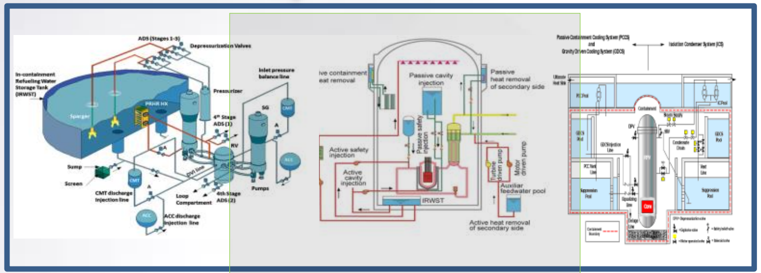
- ✓ 비상전원 제거 – Diesel generator, battery 제거
- ✓ 비상계측 제거 – Signal line 제거
- ✓ 비상작동 제거 – EOP manual 제거
- ✓ 운전판단 제거 – Human error 제거

무인, 피동 무한 냉각 개념 도입

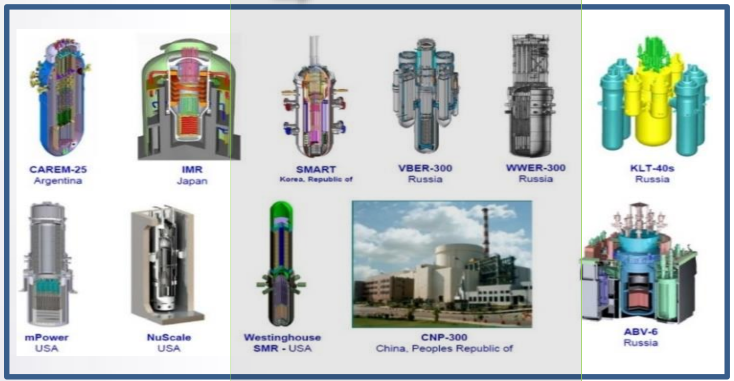
1. **Perfect Passive Drive Mechanism**
   - ✓ *Use high potential thermal energy (LOCA 시 고에너지 방출)*
2. **High Heat Transfer Mechanism**
   - ✓ *Static Pool Heat Transfer -> Dynamic Flow Heat Transfer*
3. **자연재해 또는 외부충격 근원적 해결**
   - ✓ *지하 또는 수중 설치*

PX 연구 동기

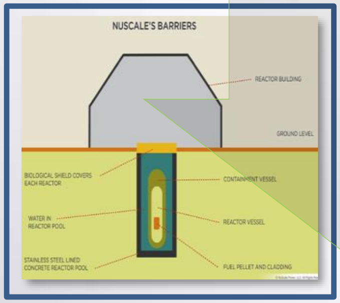
2000년대 기술적 진보 : *Passive*



2010년대 다양성 확보 : *Small*



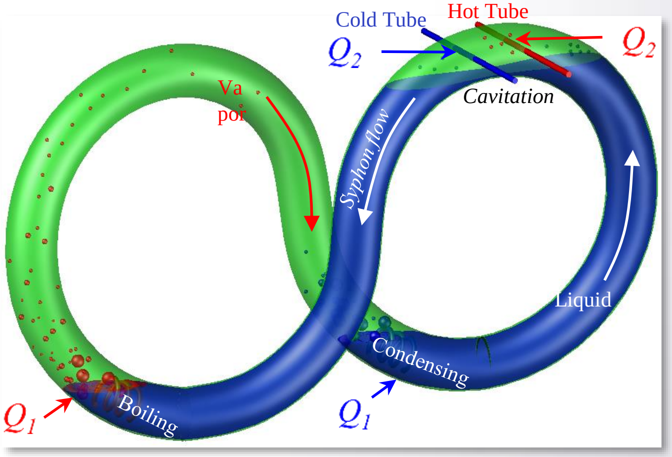
2020년대 안전성 강조 : *Safe*



PX Concept

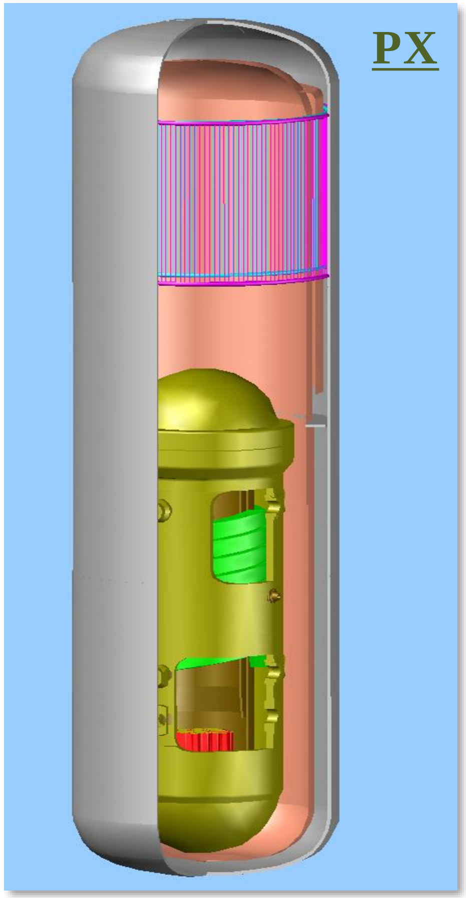
No Human Error
No Emergency Power
No Signal Cables
No Operator Decision / Action

Simple



안전성관련 사고 분류

기존 원자로 사고 분류		PX개념 사고 분류	
LOCA	Non LOCA	용기 내부 사고	용기 외부 사고
SBLOCA LBLOCA	SLB FLB TLOF SGTR SBO	SBLOCA SLB FLB SGTR SBO	



PX 유동 개념 CFD 해석

전산 수치해석(CFD)에 의한 X 순환 냉각 개념 검증