

원자로 안전을 위한 피동무한냉각 (Passive Infinite Cooling for Reactor Safety)

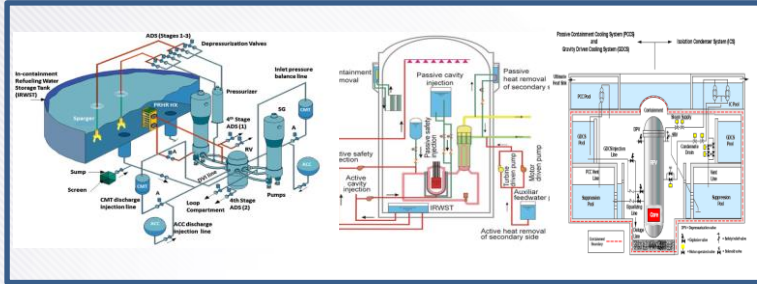
1. 개 요
2. 피동무한냉각
3. Two-step Thermosiphon
4. 격납용기 열방출 비교
5. 요 약

피동안전계통 기술혁신 워크숍, 2022년 7월 8일
한국원자력연구원 INTEC 대강당

지능형원자력안전연구소 / 혁신계통안전연구부
이성재 : sjlee2@kaeri.re.kr

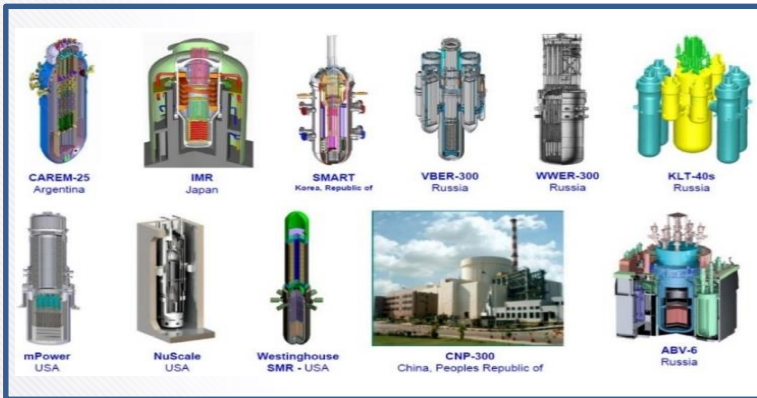
개 요 (1/2)

2000년대



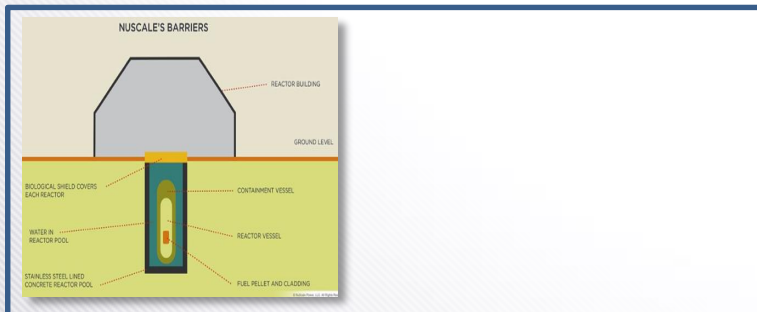
Passive

2010년대



Small

2020년대



Safe

Simple ?

No Human Error
No Emergency Power
No Safety Sensor Signal
No Operator Action

궁극적인 안전성 달성

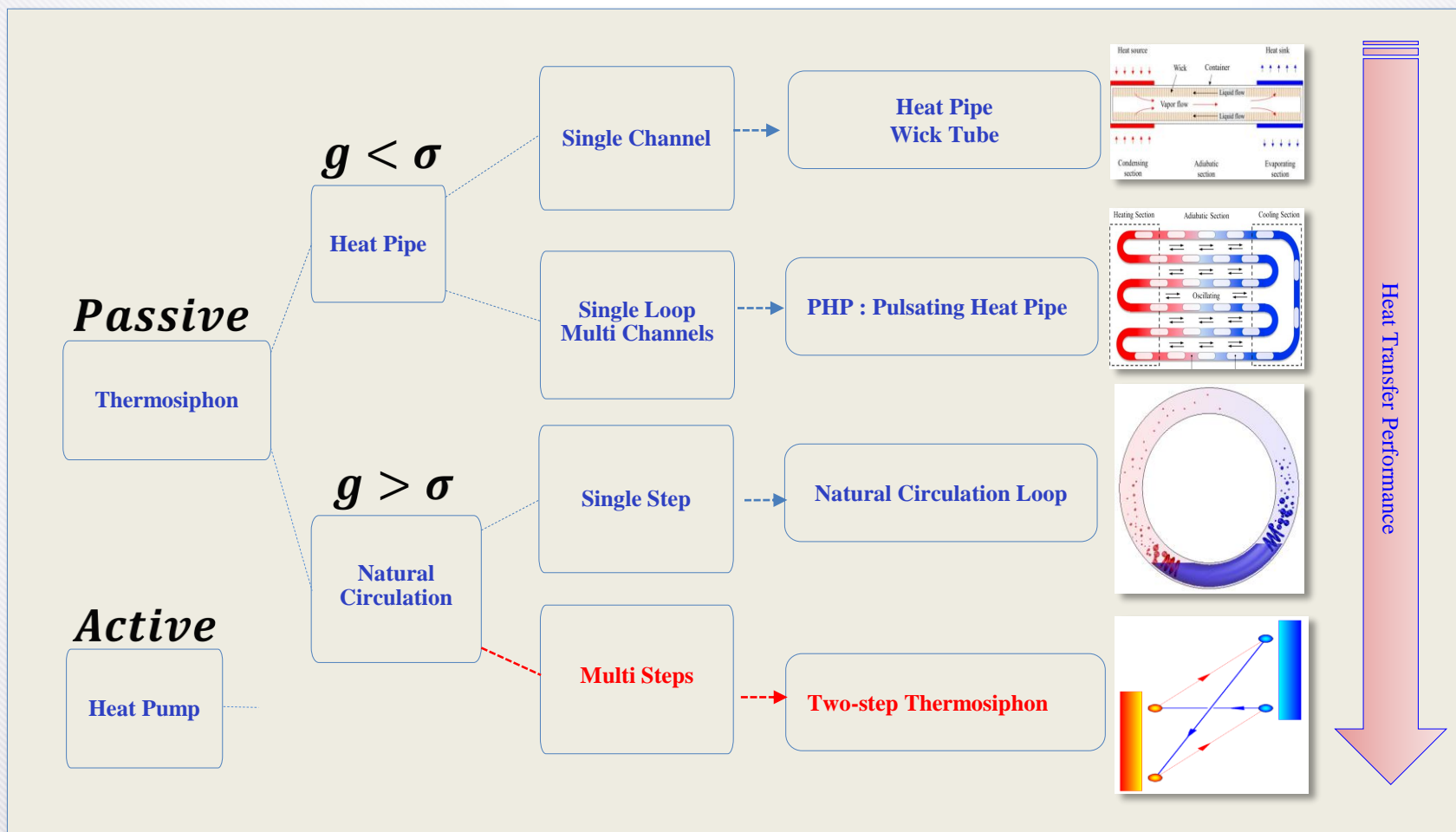
- ✓ 비상전원 제거 - Diesel generator, battery 제거
- ✓ 비상계측 제거 - Signal line 제거
- ✓ 비상작동 제거 - EOP manual 제거
- ✓ 운전판단 제거 - Human error 제거

무인, 피동 무한 냉각

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

피동 무한 냉각 (1/5)

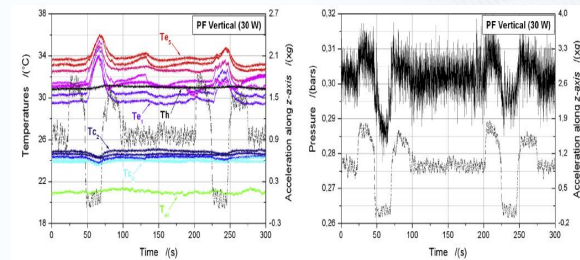
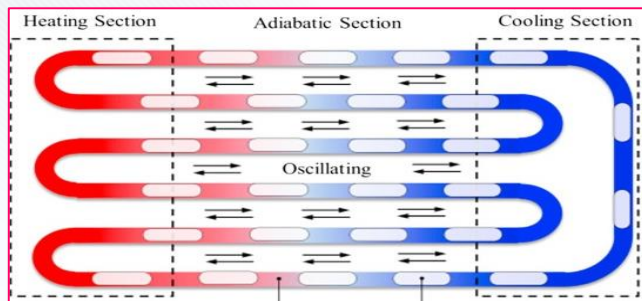
자연대류에 의한 비등 응축 열교환 방법 비교



피동 무한 냉각 (2/5)

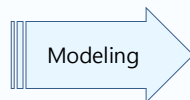
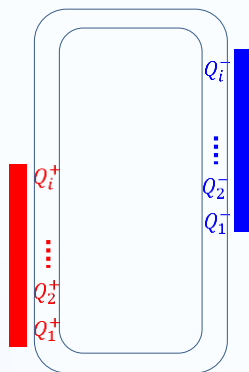
$$\sigma > g$$

- 중력보다 모세관 현상이 보다 지배적인 미세한 열전달 유로에서 열전달 과정을 실험 수행한 결과
- 유로 내부는 주로 slug 유동이며 앞뒤로 맥동을 유발하며 열전달은 약 25% 증가

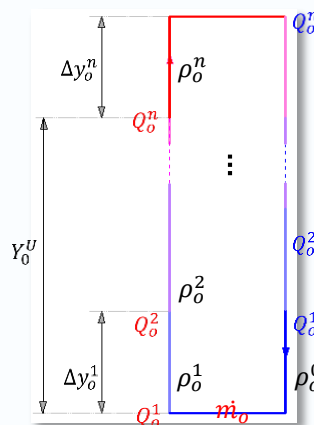


Experimental study of a closed loop flat plate pulsating heat pipe under a varying gravity force
Int. J. Thermal Sciences 96 (2015) 23-34

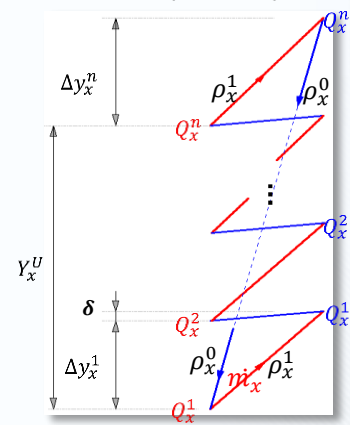
$$\sigma < g$$



Single-step thermosiphon



Multi-step thermosiphon



중력에 의한 밀도차로 자연순환이 발생하는 열전달 순환 계통에서 한번 순환시 한번의 상변화가 발생하는 경우와 여러 번의 상변화를 일으키는 순환계통의 차이를 근사적인 이론적 방법으로 비교

Saturated Liquid-Vapor Region, 근사적 이론에 의한 결과

	Multi-step thermosiphon	Single-step thermosiphon	Ratio
Momentum Balance (\dot{m})	$\oint \Delta p_x = n g (\rho_x^0 - \rho_x^1) \Delta y_x$	$\oint \Delta p_o = g (\rho_o^0 - \rho_o^n) \Delta y_o$	$\frac{\dot{m}_x}{\dot{m}_o} \approx n^{1/2}$
Energy Transfer (Q)	$Q_x = -n \dot{m}_x \frac{h_{fg,x}}{\rho_{f,g,x}} (\rho_x^1 - \rho_x^0)$	$Q_o = -\dot{m}_o \frac{h_{fg,o}}{\rho_{f,g,o}} (\rho_o^n - \rho_o^0)$	$\frac{Q_x}{Q_o} \approx n^{3/2}$

피동 무한 냉각 (3/5)

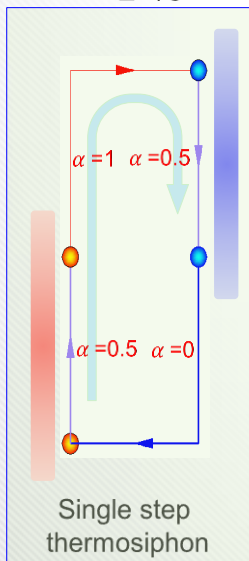
피동 무한냉각 정의: Two-steps thermosiphon

A와 B 대류 자연순환 계통 비교

1. 각 계통의 초기 조건 동일
2. 각 계통의 경계 조건 동일
3. 각 열원과 열침원 크기 동일
4. 계통의 폭은 높이에 비하여 작음

● Heating, ● Cooling, Void fraction : α

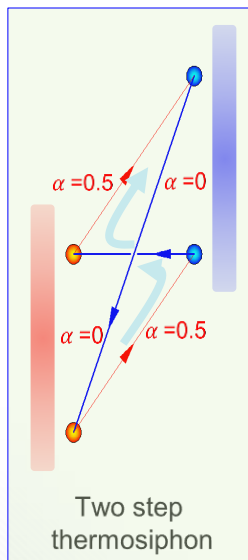
A 순환계통



A 계통 평균 기포율

$$\alpha_A = \frac{0.5 + 1 + 0.5 + 0}{4} = 0.5$$

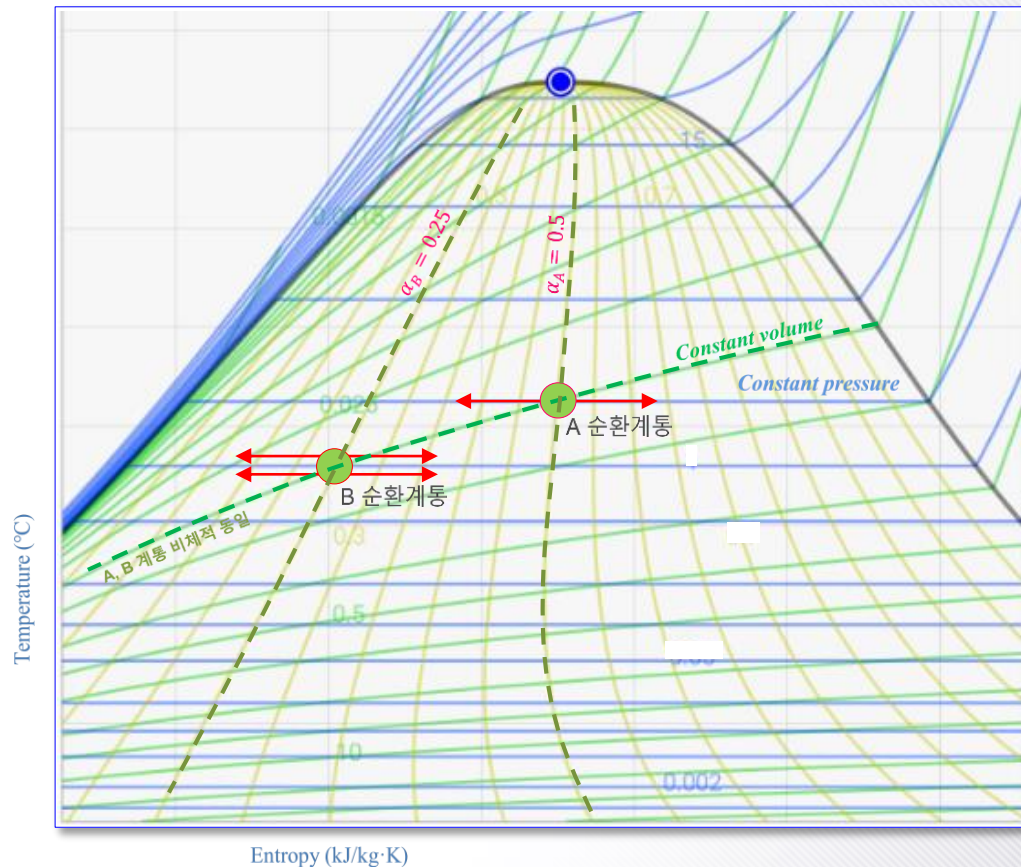
B 순환계통



B 계통 평균 기포율

$$\alpha_B = \frac{0 + 0.5 + 0.5 + 0}{4} = 0.25$$

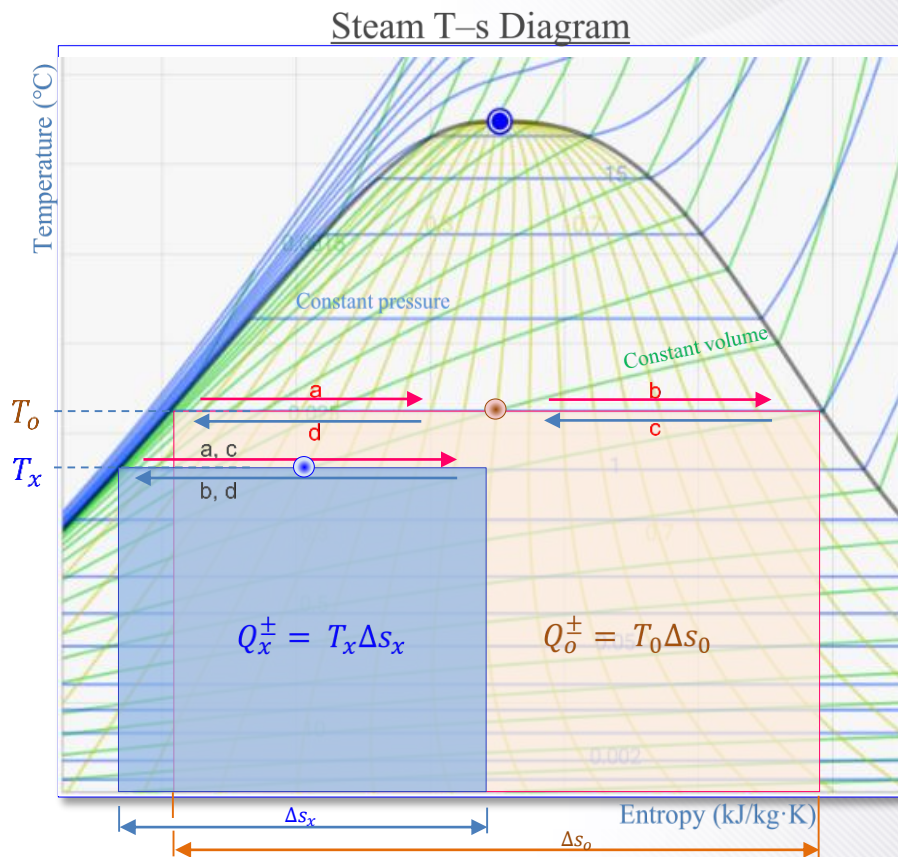
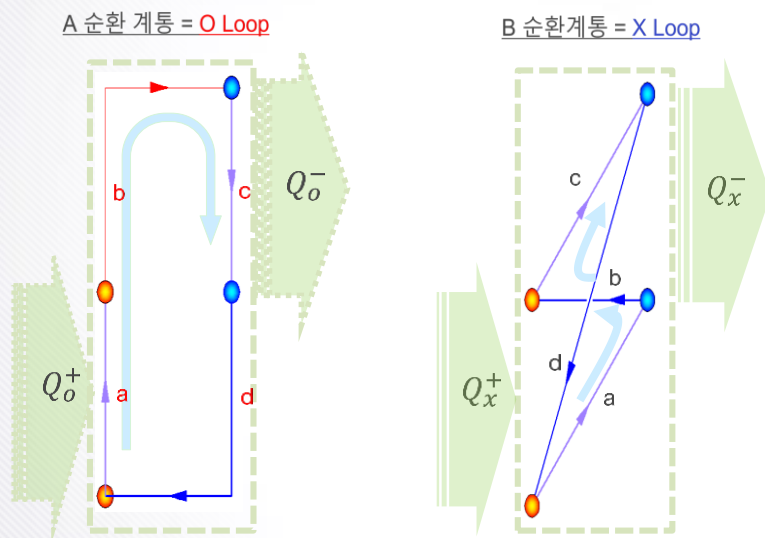
Steam T-s Diagram



각 계통에 동일한 가열과 냉각으로 최종 정상상태 도달 후 압력과 온도 상태를 증기표 상에 나타냄 (A와 B 계통의 가열/냉각율은 A계통의 상부가 완전 비등이 일어나는 조건과 동일)

피동 무한 냉각 (4/5)

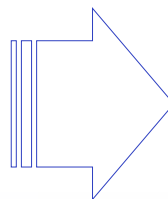
O와 X loop은 모두 같은 열량을 고온에서 저온으로 전달하지만 계통의 압력과 온도는 X loop 이 낮다. 이는 원자로 설계시 격납용기의 설계압력을 낮추는 역할을 함



두 계통의 체적, 열원과 열침원의 크기와 위치가 동일할 경우 :

Total Specific Volume : $v_o = v_x$

Total Heat Transfer : $2T_x \Delta s_x = T_o \Delta s_o$

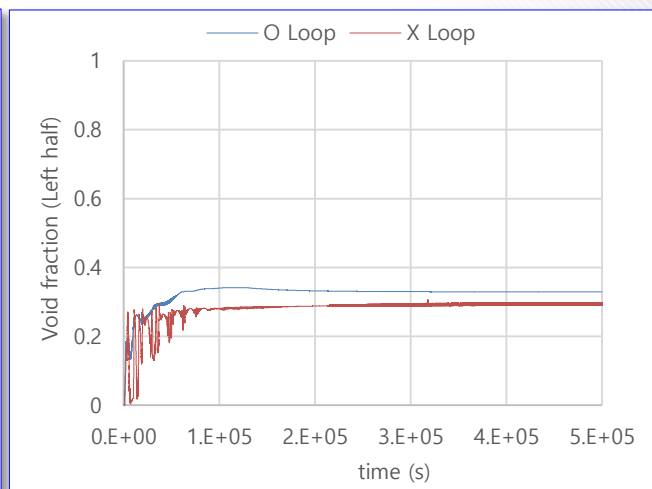
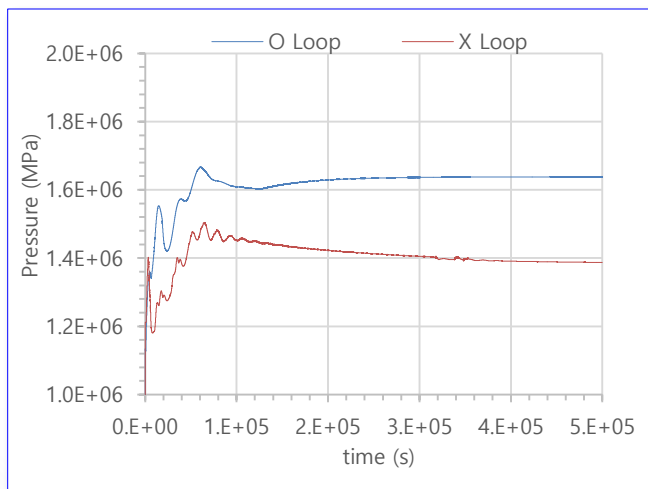
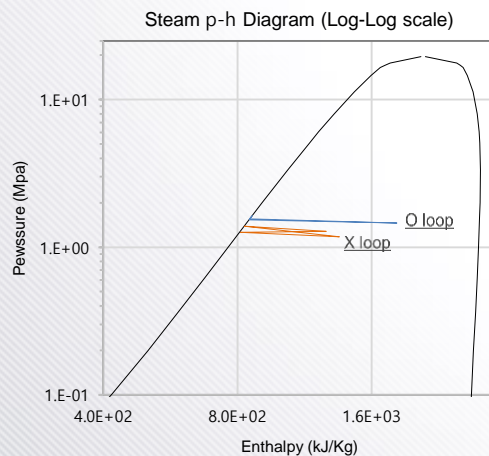
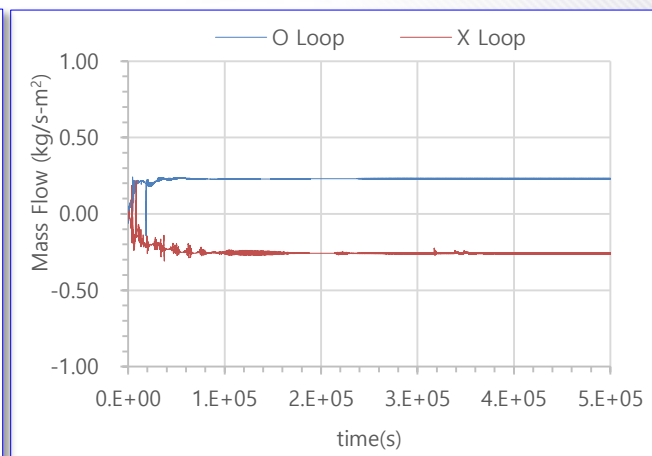
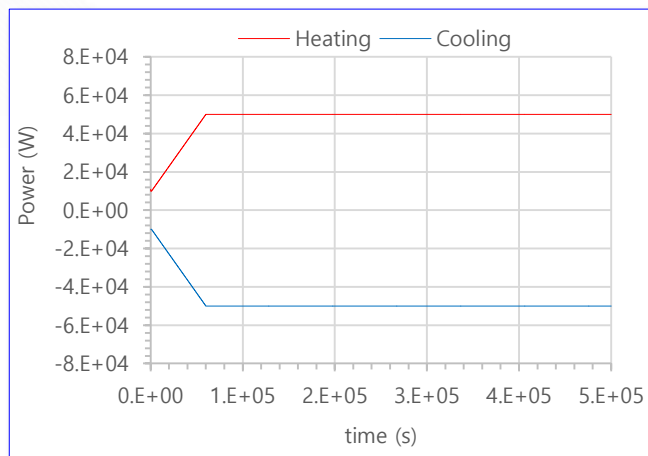
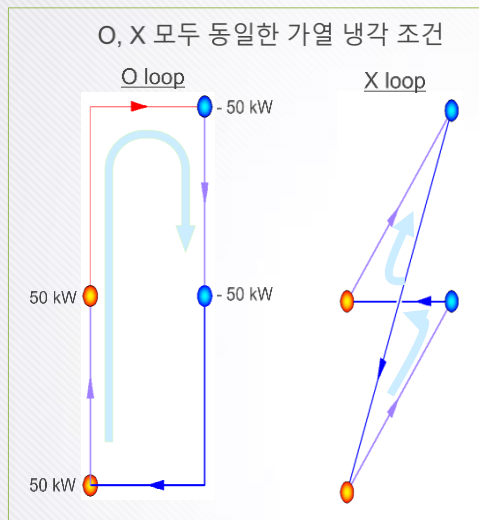


Two-step thermosiphon (X loop) 의 온도, 압력은 항상 Single step (O Loop) 보다 낮다

$$T_x < T_o$$

$$P_x < P_o$$

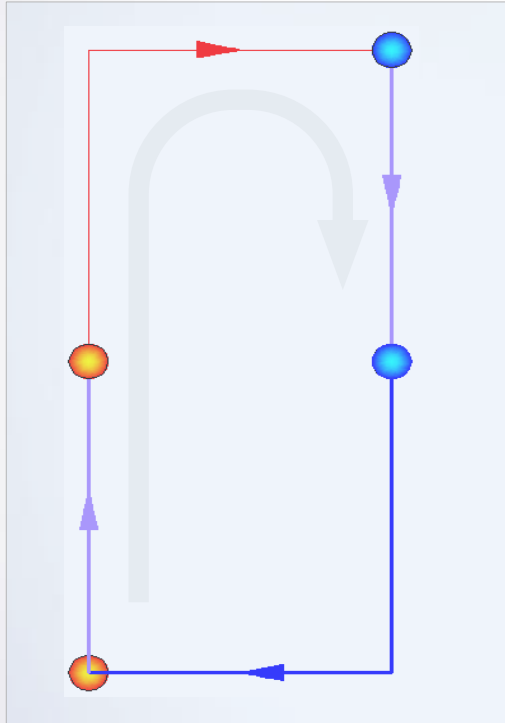
• Code Simulation Results (MARS code Ver. 1.5)



계통의 기포율이 커질수록(열출력을 올릴수록) 두 계통의 압력 차이는 더욱 확대됨

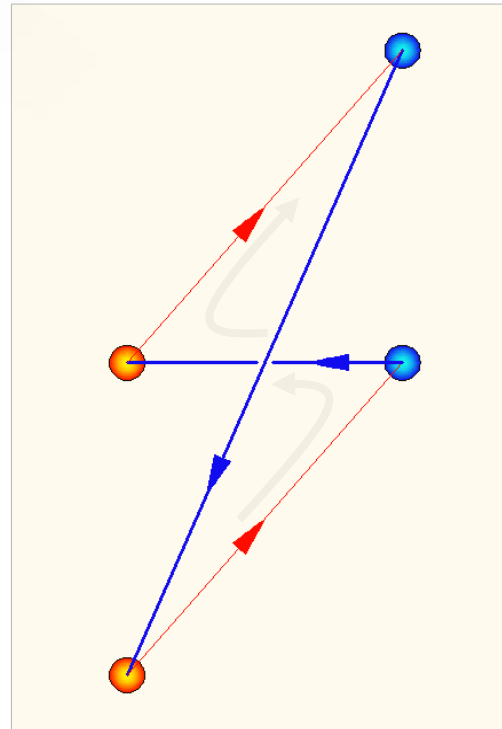
03 Two-step Thermosiphon : Circulation Concepts

Single-step
Thermosiphon

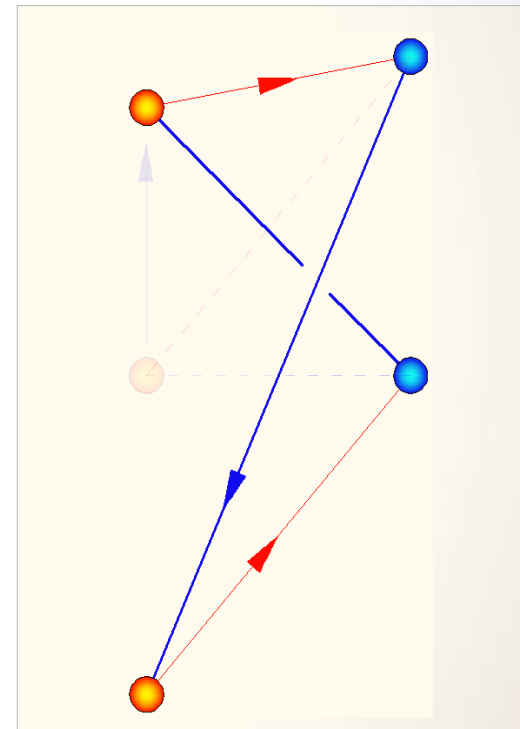


O Loop

Two-step Thermosiphon



X Loop
(Symmetric loop)



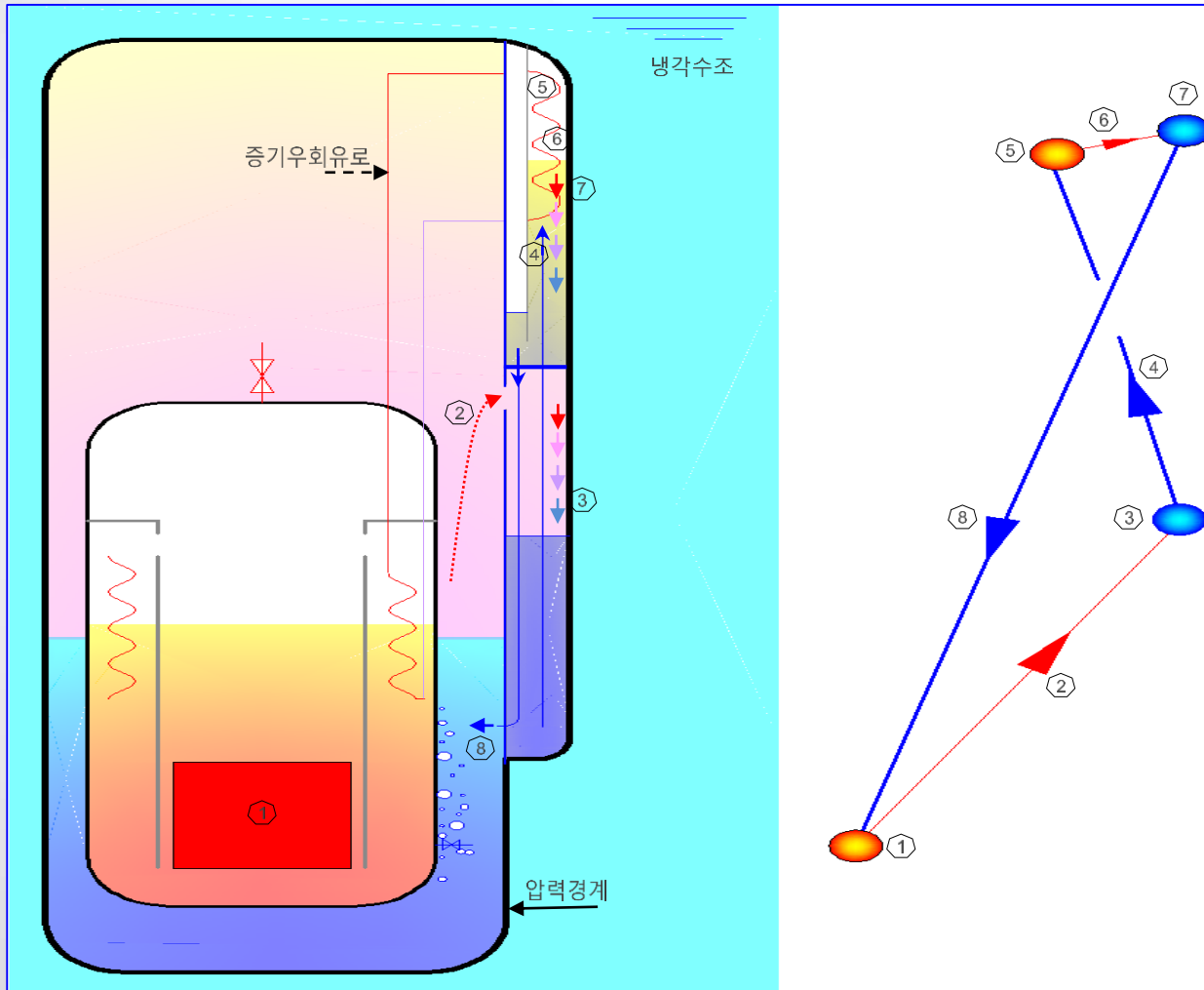
PX Loop
(Asymmetric loop)

● Heating
● Cooling

Single-step thermosiphon은 O loop이며, Two-step thermosiphon은 X와 PX loop에 해당한다.
X와 PX loop의 차이는 두번째 가열부의 위치이다. PX는 두번째 가열부가 상부로 이동한 것으로 SMR 설계에 적용할 경우 원자로 내부 증기발생기를 순환하는 잔열냉각계통 고온 튜브의 높이에 해당한다.

Two-step Thermosiphon : SMR 격납용기 적용

PX : Asymmetric Two-step Thermosiphon

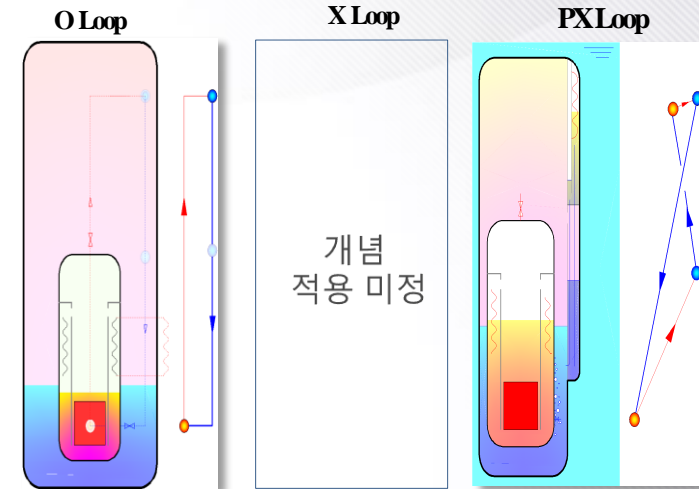


각 유로별 열수력 현상

- 1 Boiling
(Reactor wall or core)
- 2 Steam Expansion
(Outflow to containment wall)
- 3 Wall Condensation
(Containment lower wall)
- 4 Siphon Flow
(Upflow from bottom to top)
- 5 Boiling
(Tube shell side boiling)
- 6 Steam Expansion
(Tube to containment wall)
- 7 Wall Condensation
(Containment upper wall)
- 8 Return Flow
(Siphon flow to reactor bottom)

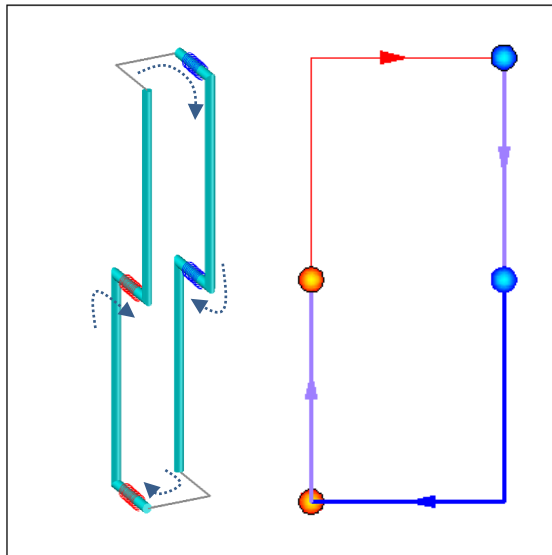
03 Two-step Thermosiphon : Loop 비교 해석 (1/3)

1. Thermosiphon 종류들의 열수력적 특성 비교를 위하여 모의 코드로 해석 수행.
2. 각 해석 모델의 부피 척도는 가상원전의 **1/100**이며 높이는 **1/1**로 보존, 초기 조건은 1MPa, 포화 액체
3. 해석 모의 가상 원자로
 - 열출력 : 250 MW
 - 크기 (H, Φ) : 20, 3 m
 - 격납용기 크기 (H, Φ) : 24, 4.5 m

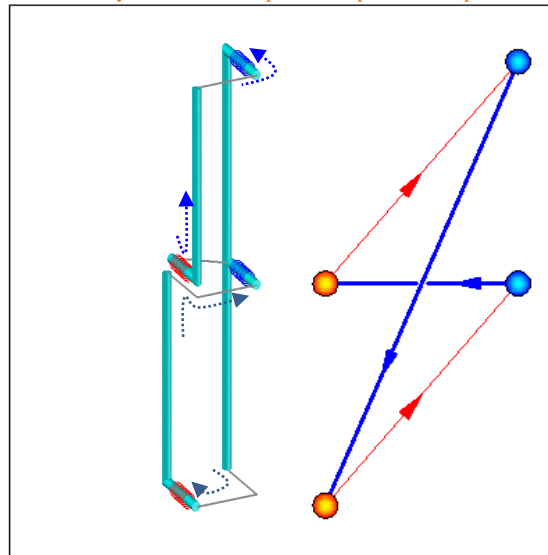


해석 모델의 3차원 형상과 내부 유동 방향

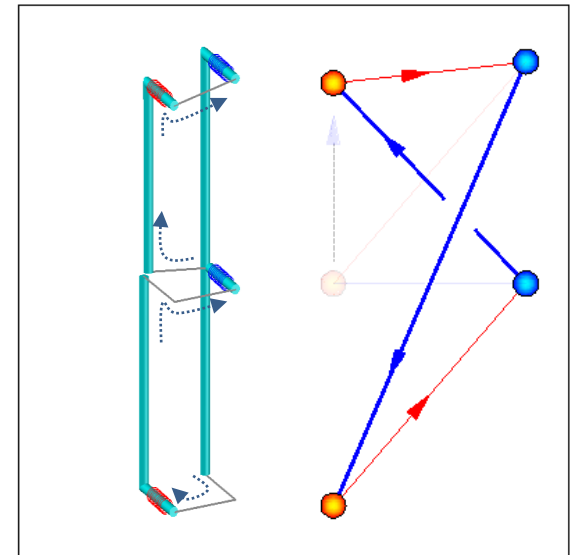
Single-step thermosiphon : O loop



Symmetric two-step thermosiphon : X loop



Asymmetric two-step thermosiphon : PX



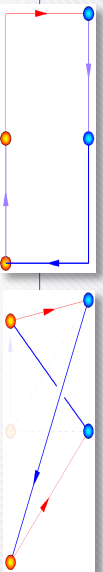
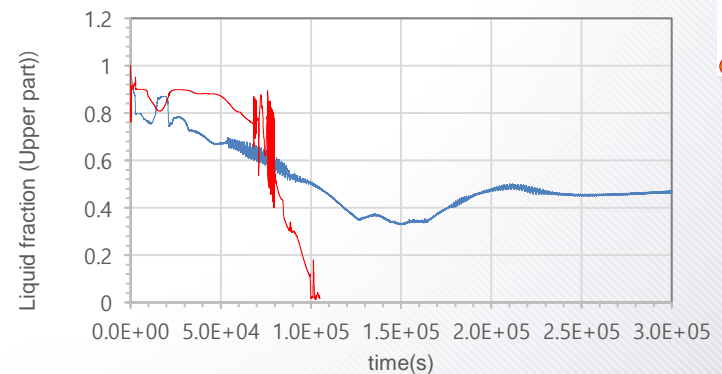
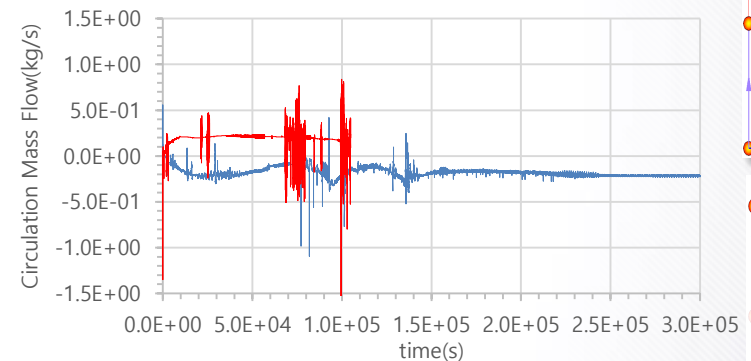
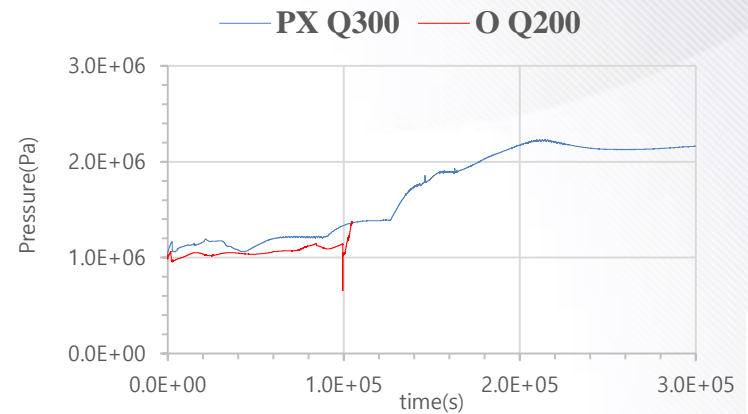
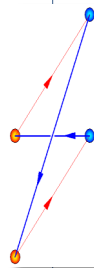
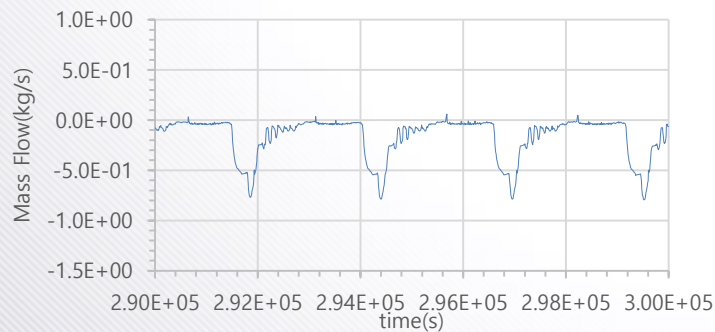
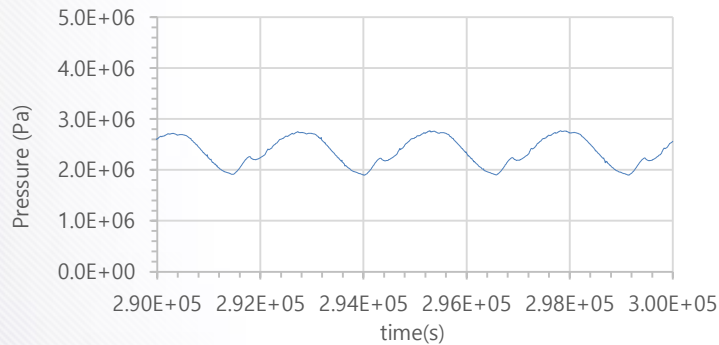
해석코드 입력에서 파란색 배관부분은 volume, 검은색 선은 junction으로 처리하여 각 Loop 모델들의 제척은 동일함, 열선달 부분은 동일 높이

Two-step Thermosiphon : Loop 비교 해석 (2/3)

출력에 따른 순환 유동 형태 비교 (Full power 2.5MW)

비등 현상	O Loop	X Loop	PX Loop	$\frac{Q_x}{Q_o}$	$\frac{Q_{px}}{Q_o}$
150kW (6%)	Stable	Stable	Stable		
200kW(8%)	Local dry out	Start Pul.	Stable		
300kW (12%)		Pulsation	Stable		
350kW (14%)		Pulsation	Local dry out		~2
450 kW(16%)		Local dry out		~2√2	

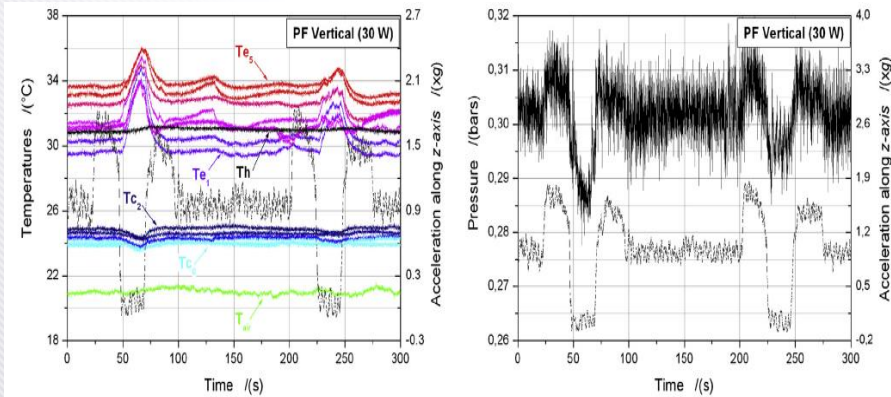
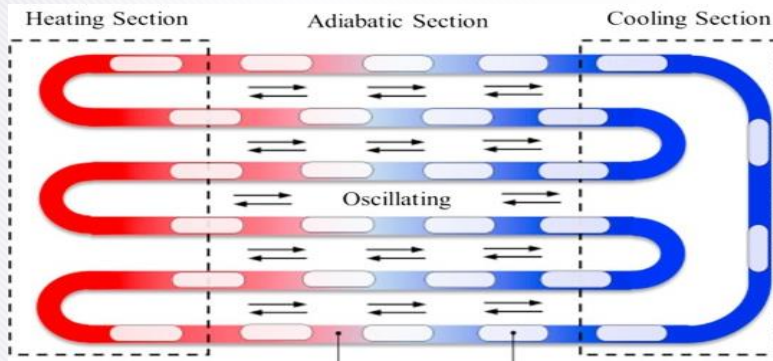
X Loop, Q 350 kW



Two-step Thermosiphon : Loop 비교 해석 (3/3)

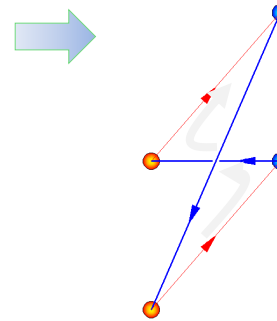
Pulsating Heat Pipe (PHP)
(Micro Channel Flow)

$$\sigma > g$$

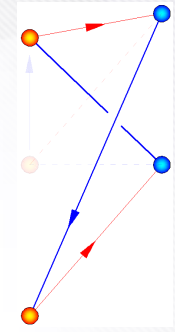
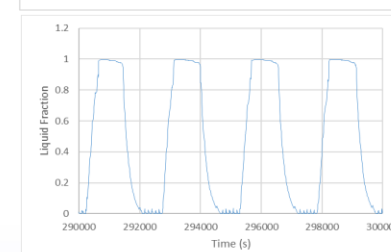
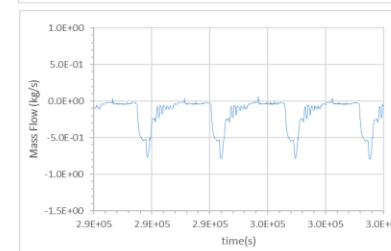
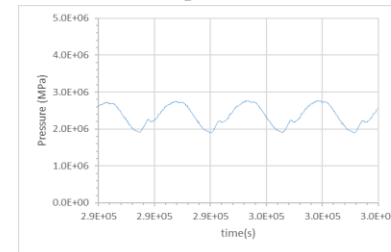


$$\sigma < g$$

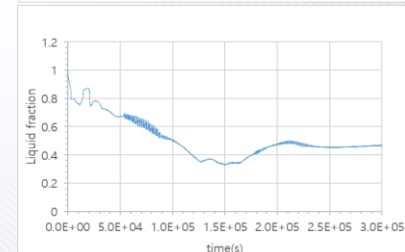
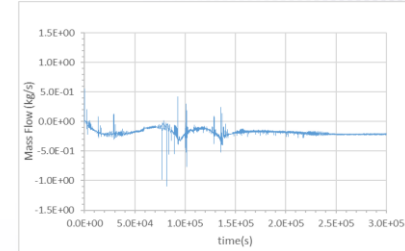
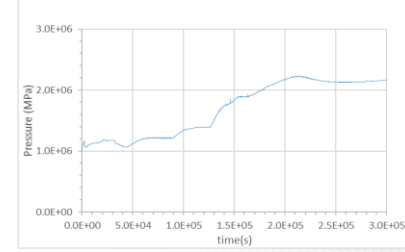
Two-step Thermosiphon



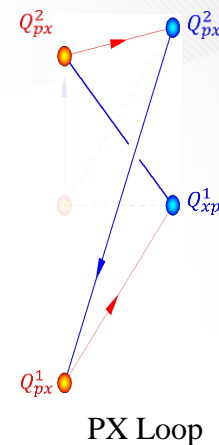
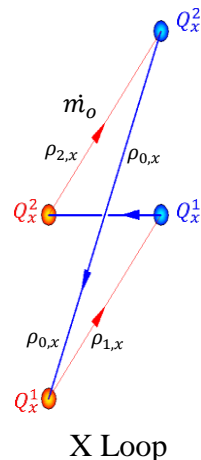
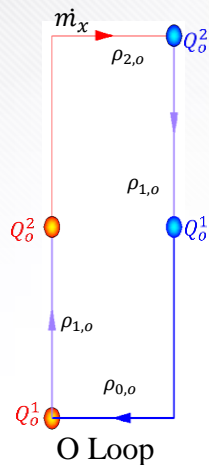
X Loop Q 350 kW



PX Loop Q 300 kW



03 Two-step Thermosiphon : 근사적 이론 비교

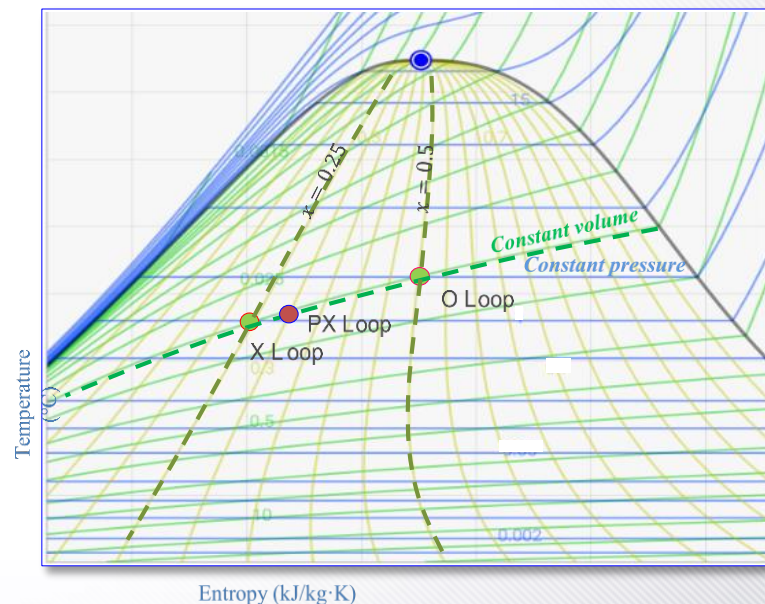


O, X, PX loop 부피는 동일하며 가열율은 모두 Loop 상부가 완전 포화상태가 되는 조건

Momentum & Energy Balance			
	O Loop	X Loop	PX Loop
Momentum Balance (\dot{m})	$\oint \Delta p_o = g \sum \Delta \rho_o \Delta y_o$	$\oint \Delta p_x = g \sum \Delta \rho_x \Delta y_x$	$\oint \Delta p_{px} = g \sum \Delta \rho_{px} \Delta y_{px}$
Energy Balance (Total Heat)	$\dot{m}_o(h_o^0 - h_o^2)$	$2\dot{m}_x(h_x^0 - h_x^1)$	$2\dot{m}_{px}(h_{px}^0 - h_{px}^1)$

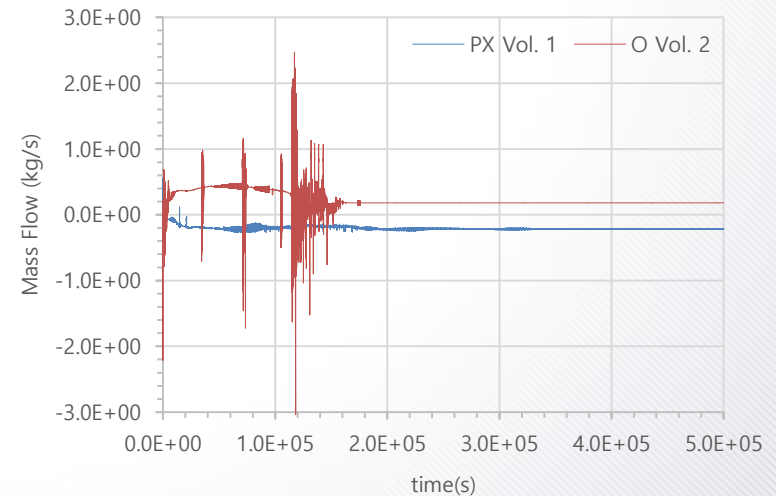
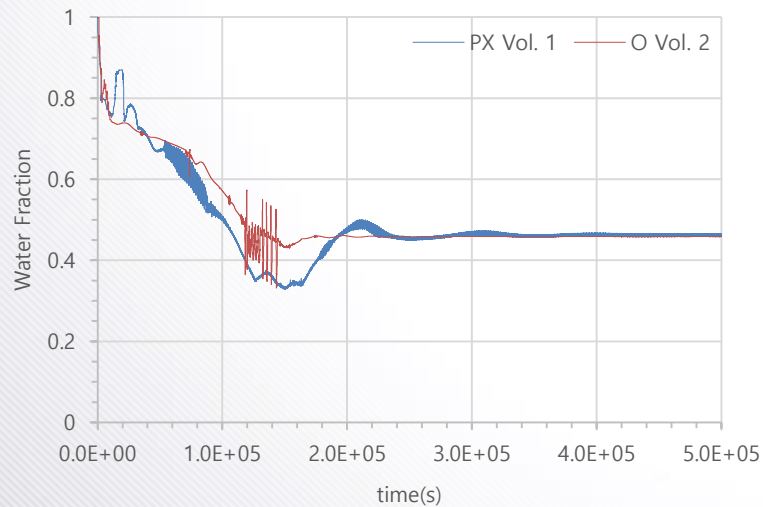
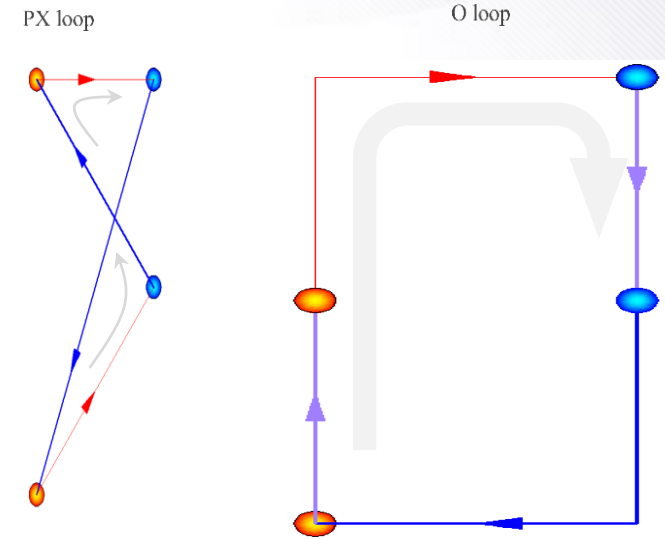
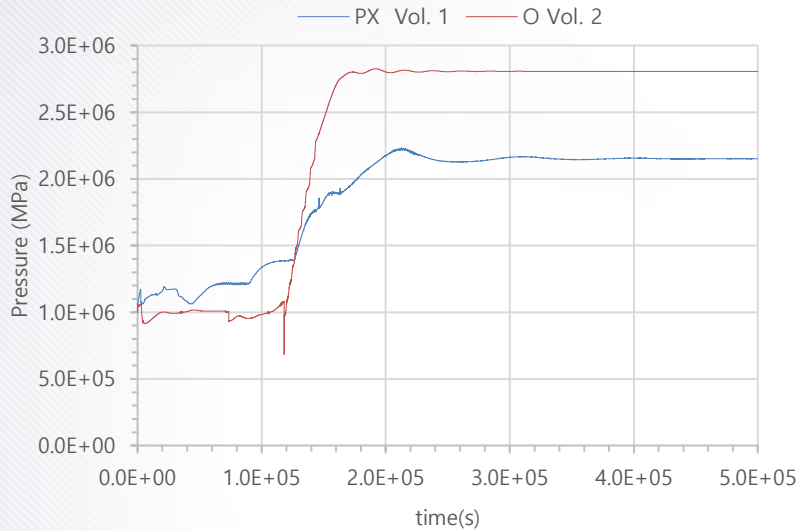
Total Loop Momentum & Energy Balance Ratios		
	X / O	PX / O
Momentum Balance (\dot{m})	$\sqrt{\frac{2(\rho_x^0 - \rho_x^1)}{(\rho_o^0 - \rho_o^2)}}, \quad \sqrt{2}$	$\sqrt{\frac{(\rho_{px}^0 - \rho_{px}^1)}{(\rho_o^0 - \rho_o^2)}}, \quad 1$
Energy Balance	$\frac{2\dot{m}_x(h_x^0 - h_x^1)}{\dot{m}_o(h_o^0 - h_o^2)}, \quad 2\sqrt{2}$	$\frac{2\dot{m}_{px}(h_{px}^0 - h_{px}^1)}{\dot{m}_o(h_o^0 - h_o^2)}, \quad 2$

Steam T-s Diagram



Two-step Thermosiphon : 축소 체적 영향 비교

O와 PX모두 동일한 (300kW) 가열, 냉각 조건 / 높이는 동일 / 체적은 OLoop이 PX보다 2배 큰 경우 해석 결과

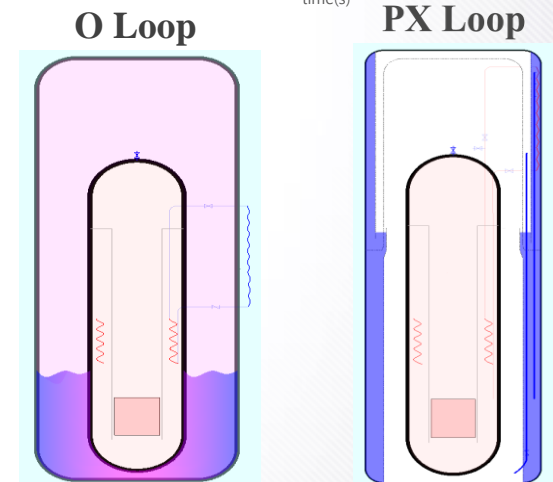
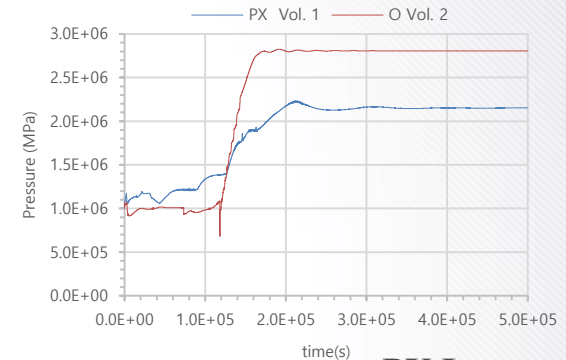


#

동일한 출력, 용기 부피 및 Pool 온도 100°C 조건

안정계통 형식		O Loop, 용기압 57 bar		PX Loop, 용기압 22 Bar			
열전달 구역	q1	q2	q1	q2	q3	q4	
열전달 조건	내외부 온도차 $T_1 - T_2$ (K)	175.60	175.60	112.00	112.00	112.00	112.00
	용기 두께 t (m)	0.1630	0.1630	0.0629	0.0629	0.0629	0.0629
	내벽 열전도* h_1 (W/m ² K)	7000.00	1000.00	10000.00	1000.00	7000.00	1000.00
	외벽 열전도* h_2 (W/m ² K)	10000.00	10000.00	10000.00	10000.00	10000.00	10000.00
	열전도 k (W/mK) Carbon steel	54.00	54.00	54.00	54.00	54.00	54.00
	길이비율	0.74	0.26	0.10	0.40	0.35	0.15
	OHTC (단위면적)	306.62	242.81	732.70	441.54	710.39	441.54
	부위별 열전달	39796.49	11122.61	11603.63	27970.15	39376.22	10488.80
	총 열전달 (단위면적)	50919.11		89438.80			

계통 비교	외부용기 직경	4.60	
	외부용기 높이	23.00	
	외부용기면적	332.21	
	열출력 (MW)		250.00
	방출열 (MW)		29.71
	출력대비 방출열 (%)		11.89
	Scale Factor 열출력비 (PX / NuScale)		체적비 (PX / NuScale) : 1 압력비 (PX / NuScale) : 1/3 열방출비 (PX / NuScale) : 1.9



$$\text{벽면 열방출량 } q \equiv \frac{T_1 - T_2}{\frac{1}{h_1} + \frac{t}{k} + \frac{1}{h_2}}$$

격납용기 벽면 열방출 비
PX / O Loop : $\frac{11.89}{6.77} = 1.8$

* : Sehmby M. S., etc, 1995, High heat flux spray cooling of electronics, 12th symposium on space nuclear power and propulsion, January 8-12, Albuquerque, NM, AIP conference proceedings, Vol. 324, pp. 903-909.

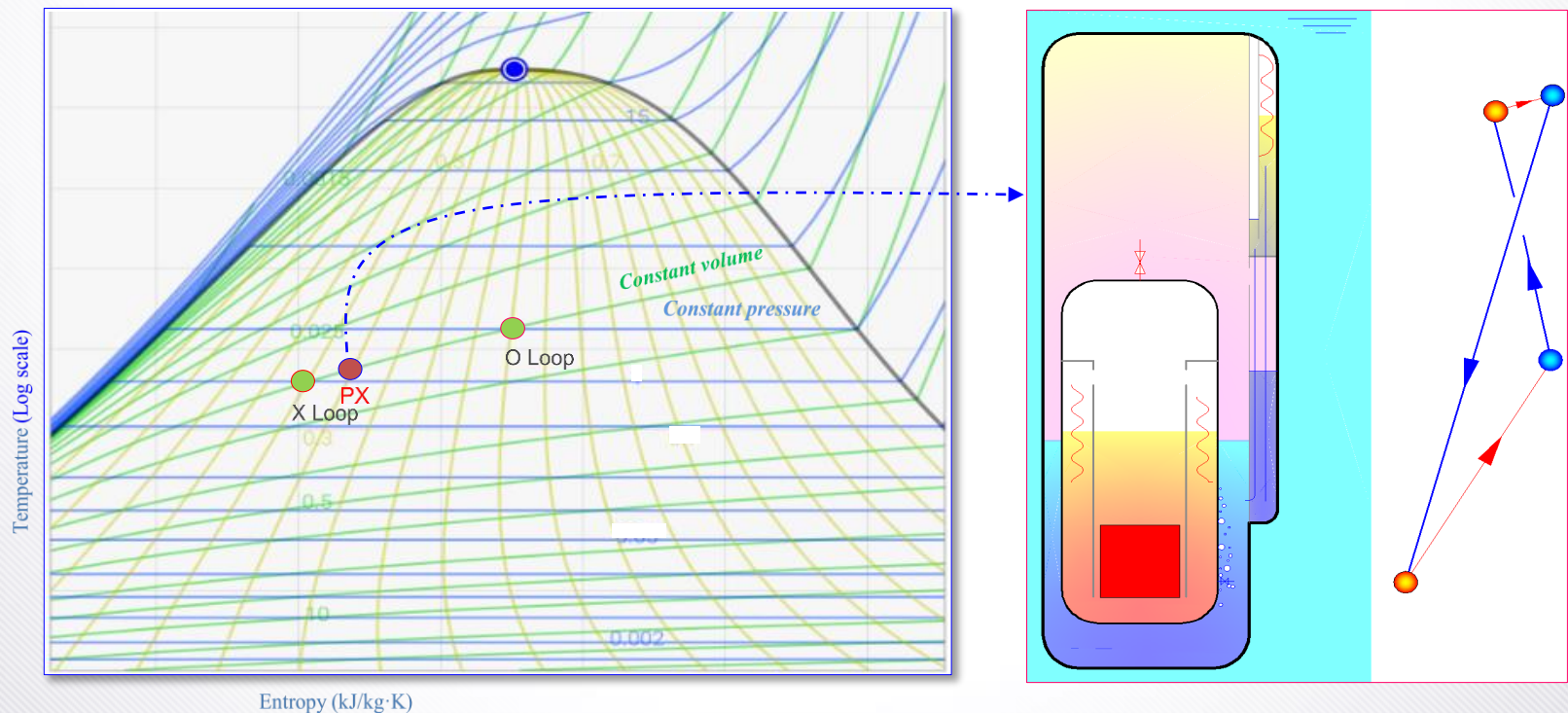
* : Morgan M. J., Chang W. S., Pais M. R. and Chow L. C., 1992, Comparison of high-heat flux cooling applications, Proceedings of SPIE-the international society for optical engineering, Paper No. 1739-02.

* : Yang J., Pais M. R. and Chow L. C., 1993, Critical heat flux limits in secondary gas atomized liquid spray cooling, Experimental Heat Transfer, Vol. 6, pp. 55-67.

피동무한냉각(PX)의 격납용기 적용

- Asymmetric Two-steps Thermosiphon
- Lower Steam Pressure & Temperature

Steam T-s Diagram

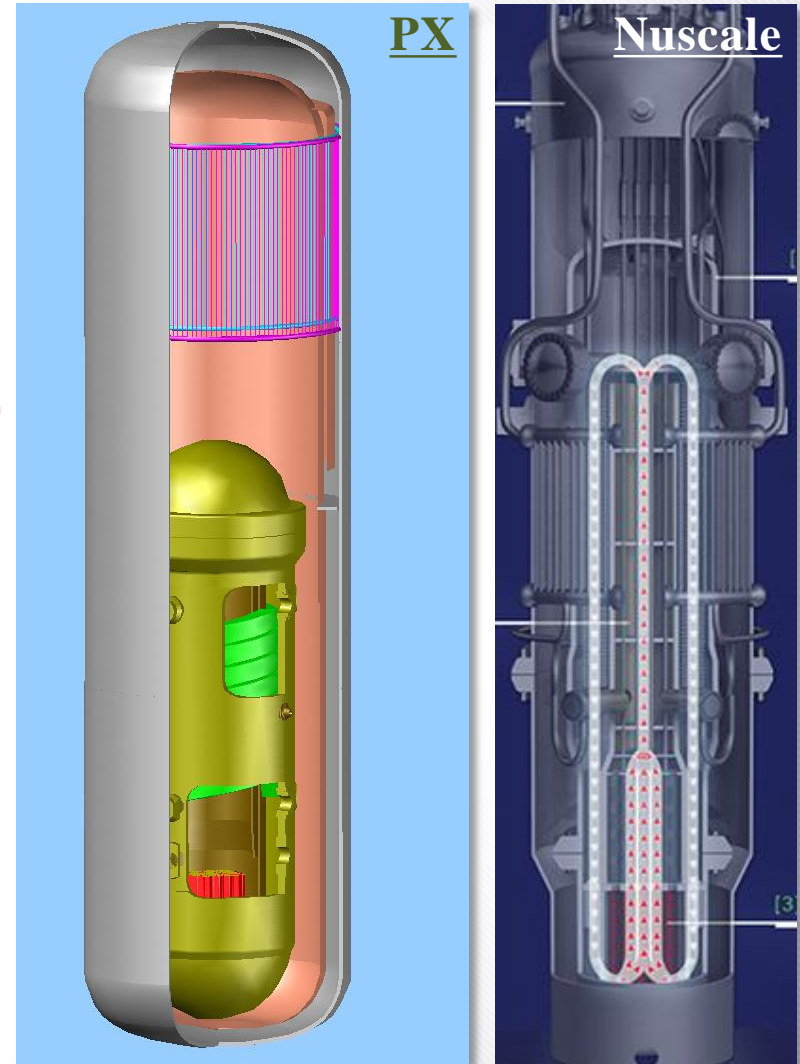


피동무한냉각(PX)의 격납용기 적용

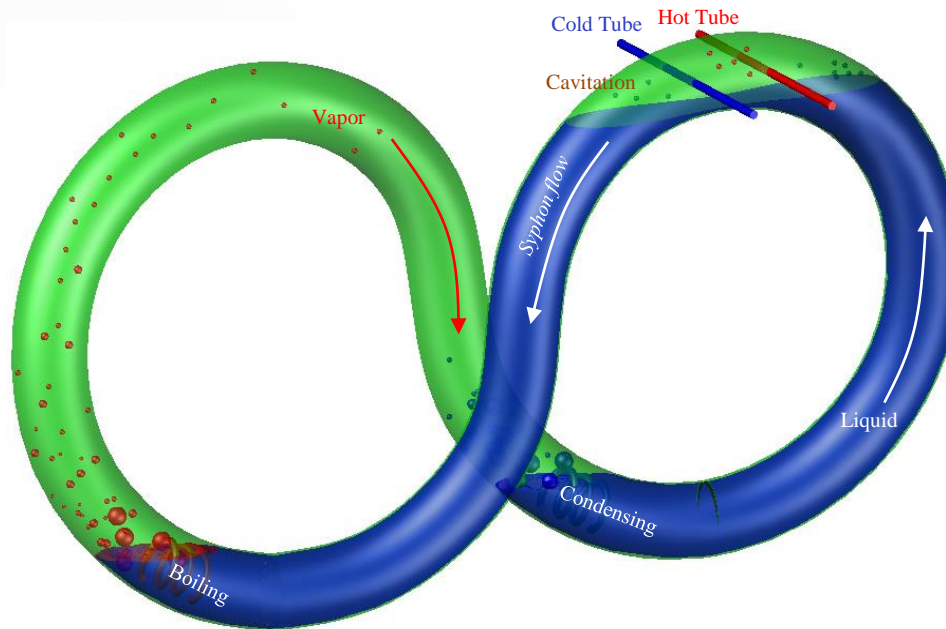
1. 출력당 작은 부피와 낮은 압력 구현
2. 격납용기 두께 감소로 용이한 설계
 - 벽면 열방출 효과 증대
 - 열팽창 흡수 능력, 관통기기 단순화, 제작/이송 용이
3. 잔열제거계통의 내부 배치로 관통 배관 제거

PX와 NuScale의 주요 차이

	PX	NuScale
구조	용기 내부 PRHR	용기 외부 PRHR
열수력	용기 압력 : 2 MPa	용기 압력 : 6 MPa



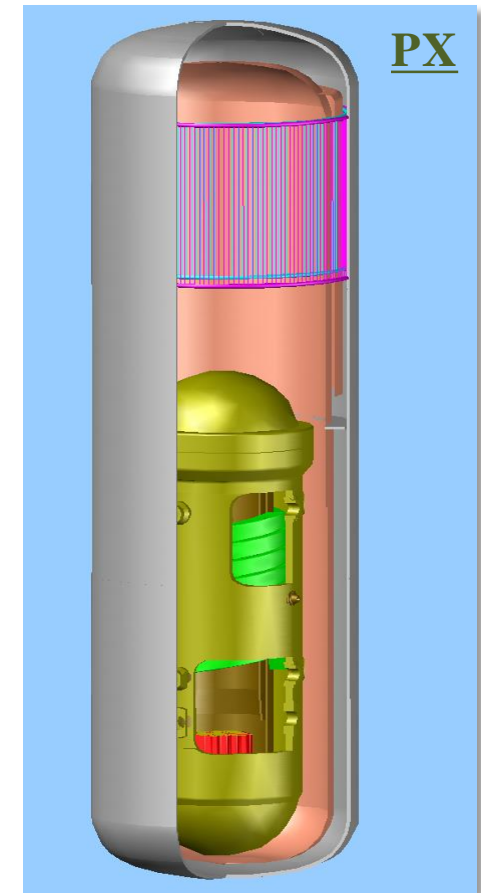
참고 자료



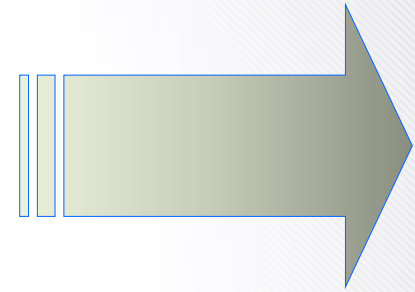
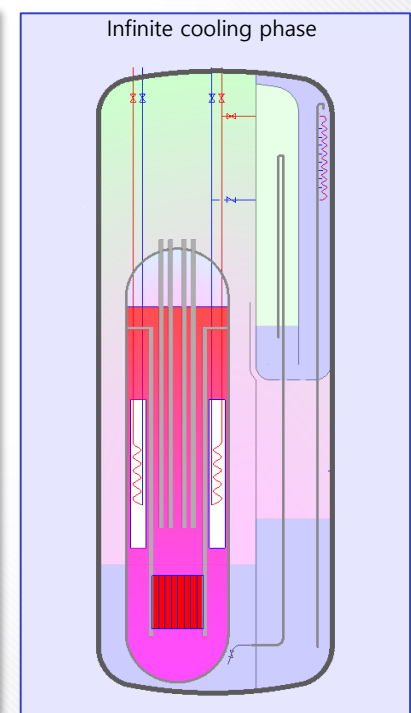
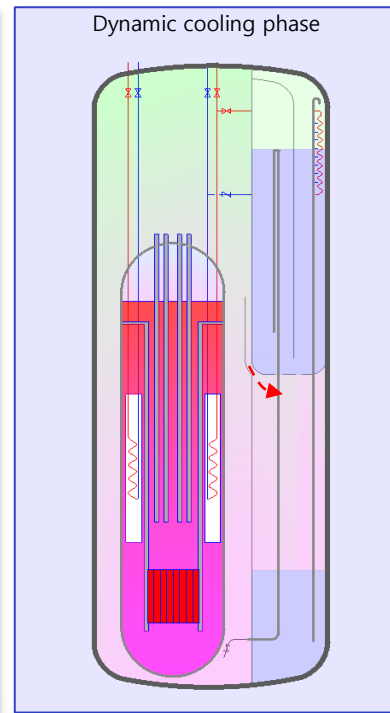
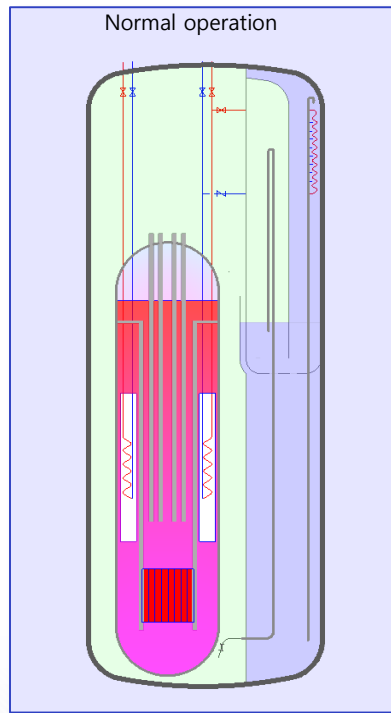
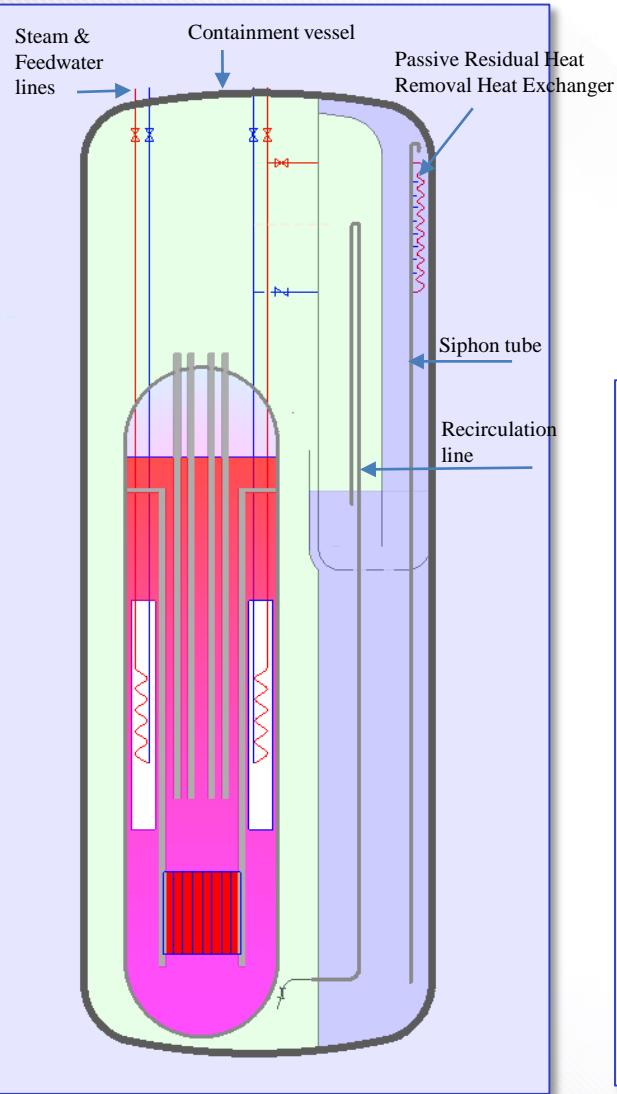
PX : Passive Infinite Cooling
(Asymmetric Two-step Thermosiphon)

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	
안전주입	안전감압	안전감압 및 재순환	

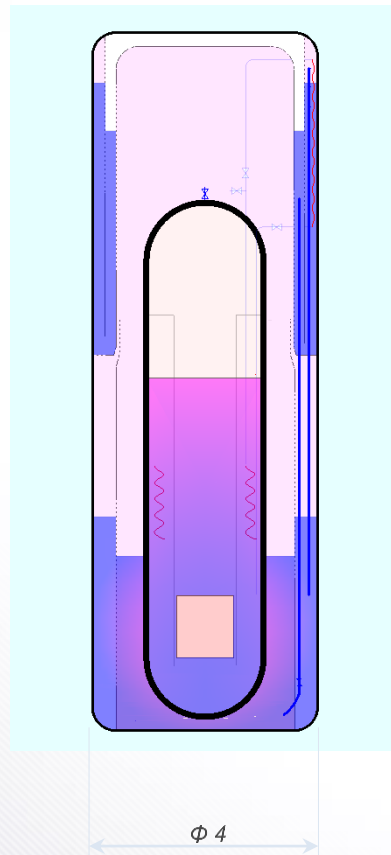


04 PX 유동 형성 및 장기 순환 개념

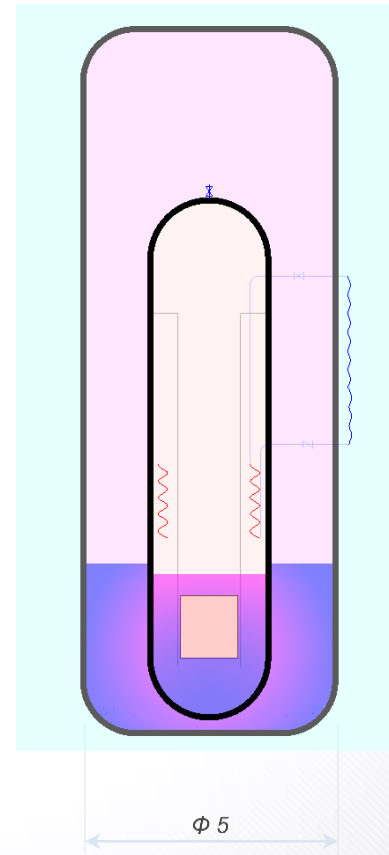


PX와 O loop 개념 적용 격납용기 비교

1. SB-LOCA
2. Internal PRHR
3. CV Design P. ≈ 2 MPa
4. CV Thickness ≈ 6 cm

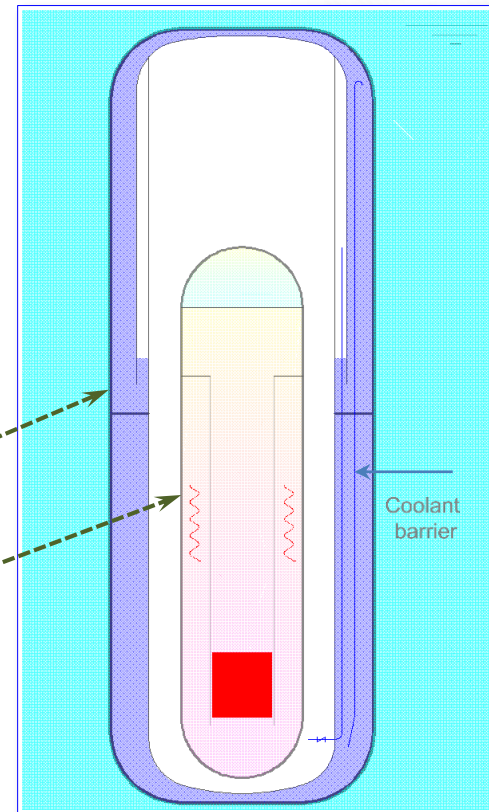
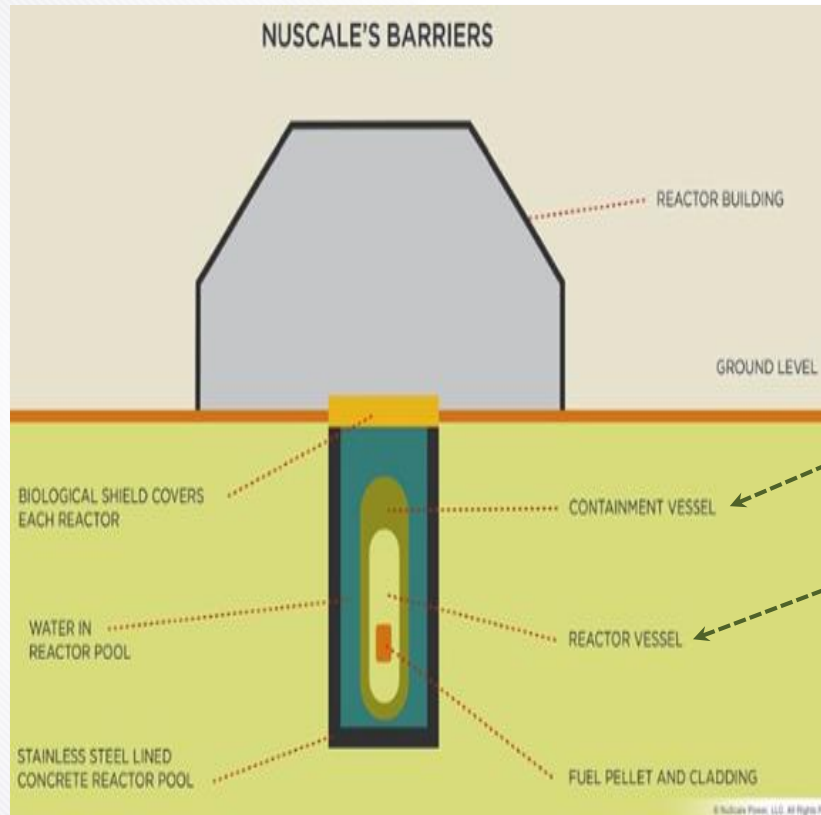


1. LB-LOCA
2. External PRHR
3. CV Design P. ≈ 6 MPa
4. CV Thickness ≈ 18 cm



Rx Power : 250 MWt
Rx D. : 2.7
Rx H. : 20.2
CV H. : 23.2

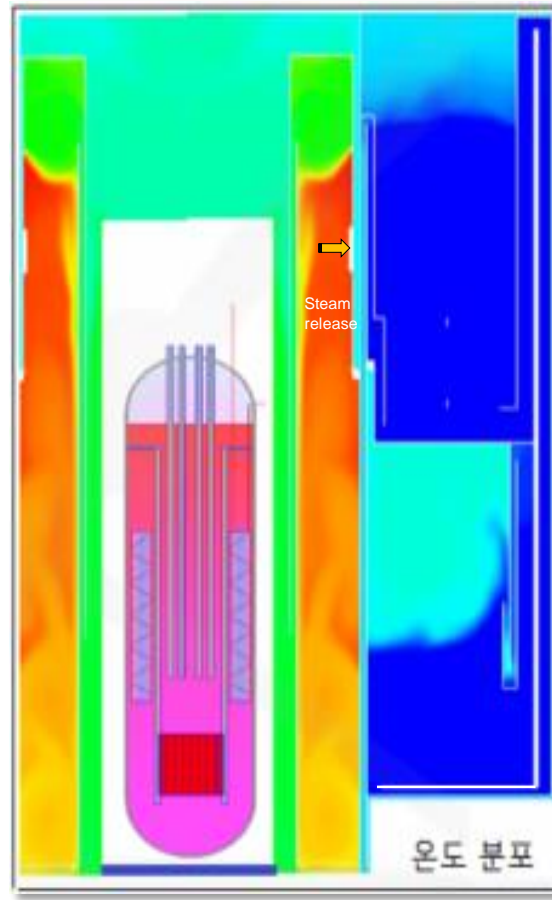
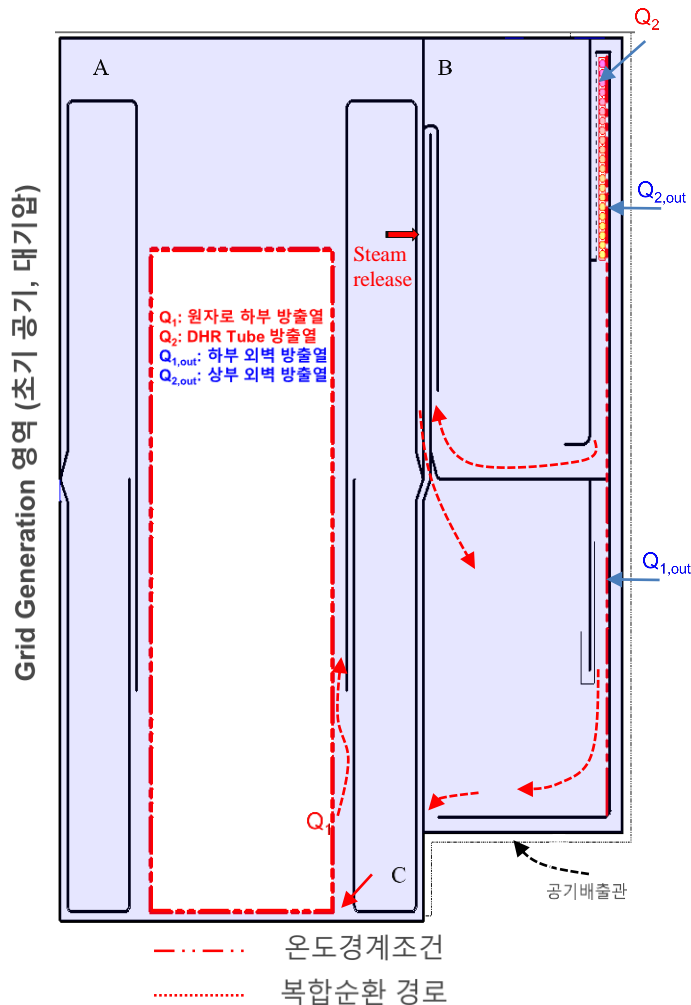
PX & NuScale 심층 방어 개념



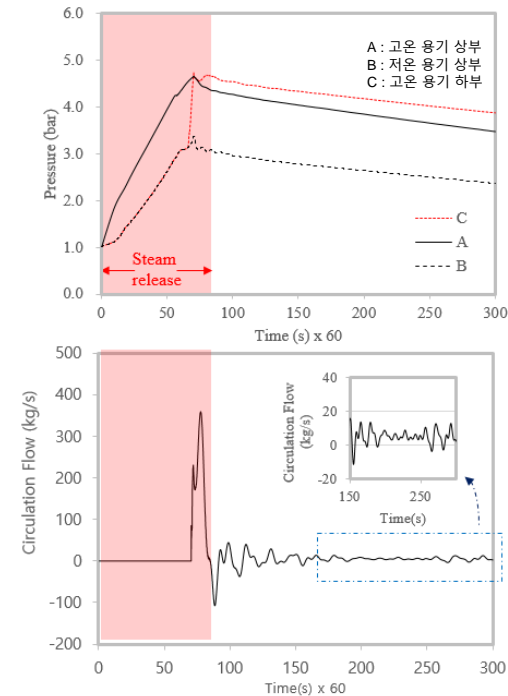
PX 유동 CFD 예비 해석

» 전산 수치해석(CFD)에 의한 χ 순환 냉각 개념 검증

* SMART-ITL CLOF 사고를 경계조건으로 활용 (원자로 외벽온도, DHR 튜브온도)



PX 안전계통
2차원 열수력 거동 전산수치해석 결과



전산수치해석 결과에 따른
용기 내부 압력 및 순환 유량