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STUDY ON AIR INGRESS PROCESSES DURING A DEPRESSURIZATION ACCIDENT OF VHTR

Contents

1. Introduction
2. Experimental apparatus and numerical model
3. Experimental and numerical results and discussion
4. Conclusions

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International Conference on High Temperature Reactor Technology HTR 2018,
October 8-10, 2018, Warsaw, Poland

Back ground and objective

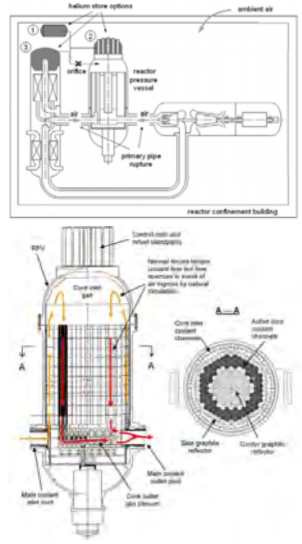
The objective of this study are to research gas mixing process and to develop the prevention technology of air ingress.

It is necessary to prevent air Ingress or oxidation of graphite at pipe rupture accident of Very High Temperature Reactor.

Even if the pipe rupture accident occurs, ingress of air can prevent by injecting helium gas.

Air ingress scenario in the case of the horizontal pipe break

1. *Pipe rupture at connecting pipe between RPV and gas turbine.*
2. *Helium gas blows off from the RPV.*
3. *Pressure in the reactor equalized to the one in the containment or confinement vessel.*
4. *Buoyancy force produce by the temperature difference between inside and outside passage in the RPV.*
5. *Natural circulation of air will produce. (depend on temperature profile or geometrical condition)*
6. *Graphite of reactor component will react with ingress air.*



Schematic diagram of GTHTR300C
Designed by JAEA

Back ground

It is necessary to prevent air Ingress or oxidation of graphite at pipe rupture accident of High Temperature Reactor

Air Ingress Scenario in the case of the horizontal pipe break

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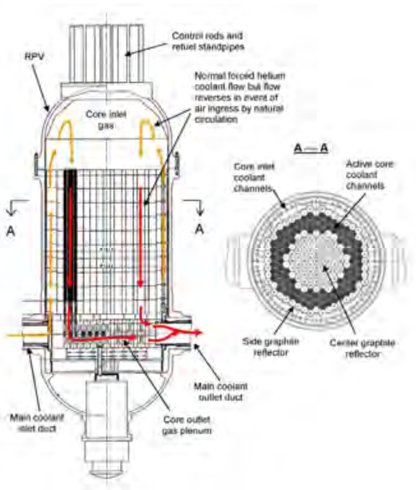
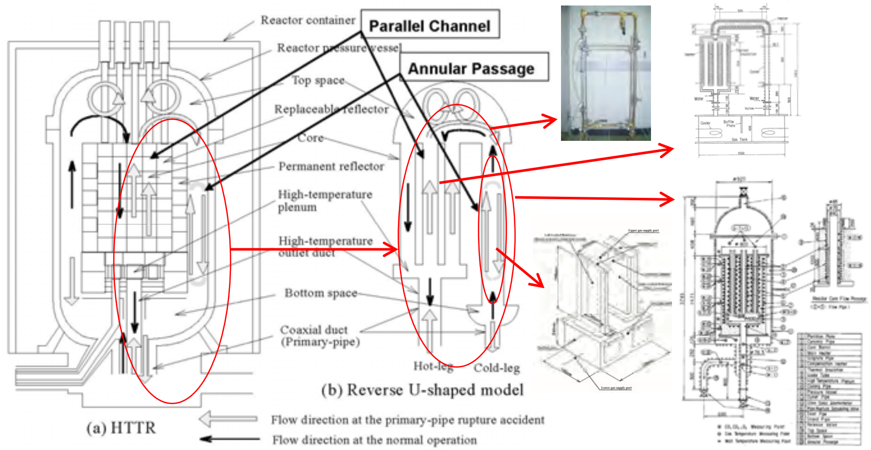


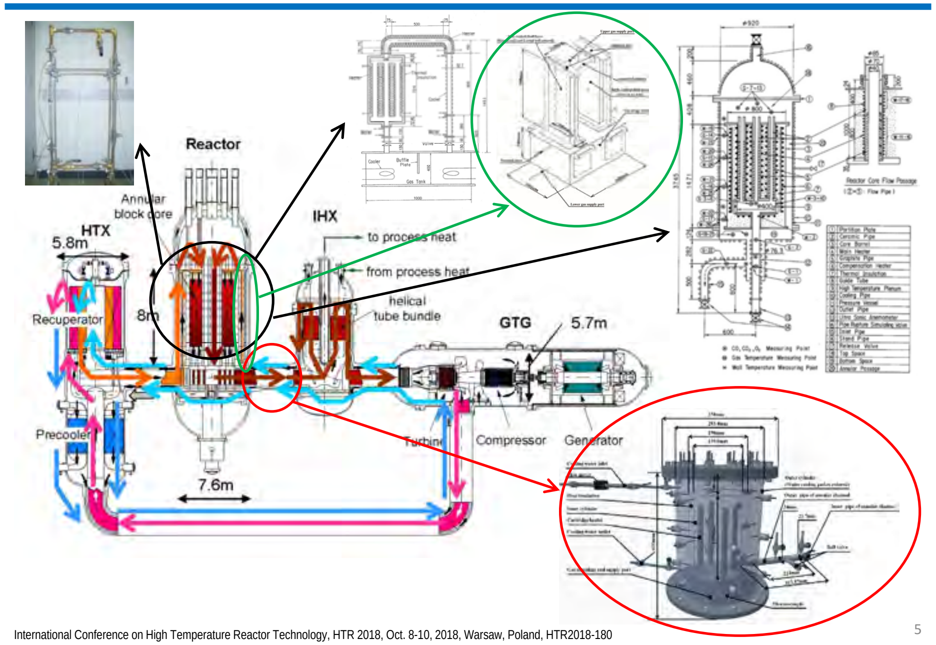
Schematic diagram of GTHTR300C
Designed by JAEA

Schematic drawing of the HTTR and model of coolant passages

- *A hot leg consists of an inner passage of a coaxial duct, a high-temperature outlet duct, a high-temperature plenum and fuel cooling channels.*
- *A cold leg consists of an annular passage of the coaxial duct, a bottom cover and an annular passage between the reactor pressure vessel and permanent reflector.*
- *As the hot and cold legs are connected at the top space, they make a kind of reverse U-shaped tube.*



Schematic drawing of the GTHTR300C and model of coolant passages



Influence that localized natural convection in the vertical channels with different temperature exerts on onset time of natural circulation

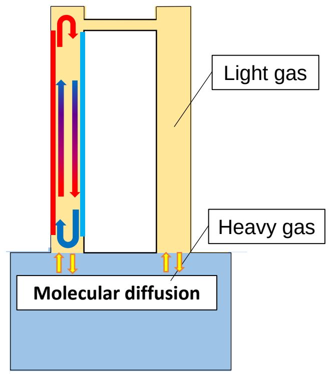
The experiment has been carried out to research mixing process of two component gases and onset time of natural circulation of air.

When one side wall is heated and the other side wall is cooled in a vertical slot, a localized natural convection is generated.

Heavy gas will diffuse into the both vertical slots at the same time, and then time elapsed, natural circulation through the passage will be generated finally.

Purpose of this study

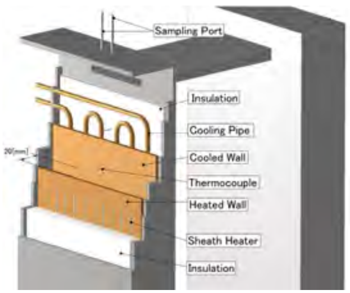
To investigate an onset time of natural circulation and a mixing process of two component gases by using 3D numerical analysis.

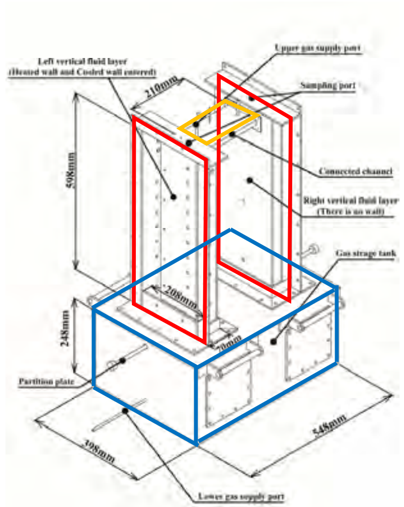


The flow regime of this localized natural convection is ranging from conduction regime to boundary layer regime.

Experimental apparatus

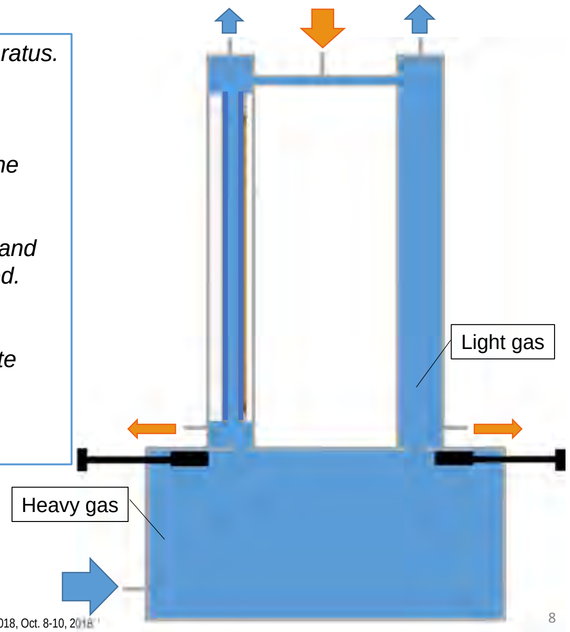
- *The apparatus consists of two vertical slots, connecting passage and storage tank.*
- *Vertical slots and storage tank were separated by partition plate.*
- *The left side vertical slot consists of a heated wall and a cooled wall.*
- *The right side vertical slot consists of two cooled walls.*





Experimental procedure

1. *Heavy gas is filled with apparatus.*
2. *Partition plate close.*
3. *Light gas inject from top of the apparatus.*
4. *Two vertical wall of the left hand side slot is heated and cooled.*
5. *When the steady state was established, the partition plate open.*
6. *Experiment starts.*



Numerical model

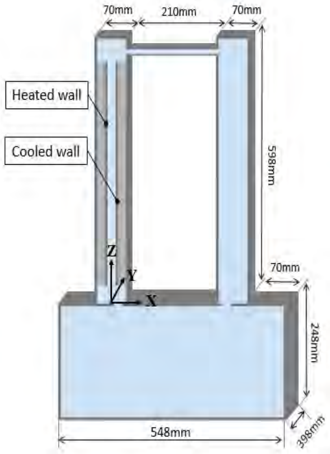
PHOENICS: three-dimensional CFD code

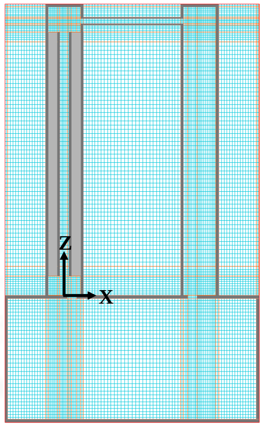
◆***Analytical domain***
X : 548, Y : 398, Z : 846 mm

◆***Analytical grid***
x: 122, y: 20, z: 118 (total cells : 266680)

◆***Boundary condition***
The outside of the heated wall and the cooled wall assumed an adiabatic wall. The other walls assumed natural convection heat transfer boundary condition.

◆***Others***
Standard density : ρ_0
→ *Buoyancy :* $(\rho-\rho_0)gV$





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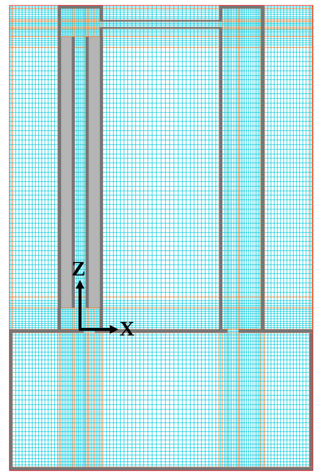
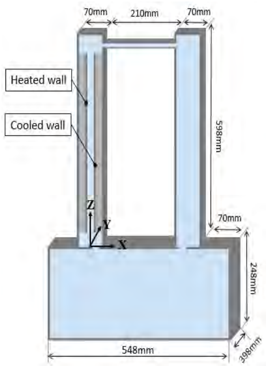


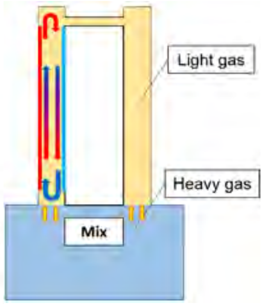
Numerical method

◆***Numerical method:***
1. Steady state calculation:
Natural convection was generated by temperature difference between the vertical walls.
2. Unsteady state calculation:
Partition plate was opened at 0 sec.
Calculation step :0.01sec/step･･･ 0~10sec
0.05sec/step ･･･ 10sec~

◆***Initial condition of steady state:***
Heavier and lighter gases were filled.
The vertical walls of the left side slot was heated and cooled.

◆***Initial condition of unsteady state:***
The result obtained by steady state calculation.





Gases	Density [kg/m 3] (20ºC, 1atm)
Helium (He)	0.164
Neon (Ne)	0.838
Nitrogen (N2)	1.17
Argon (Ar)	1.64

Two component gases (light-heavy)	Diffusion coefficient [cm²/s]
N_2-Ar	0.20
Ne-Ar	0.32
He-N_2	0.68
He-Ar	0.73

Two component gases and temperature difference

Gases	Density [kg/m 3] (20ºC, 1atm)
Helium (He)	0.164
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Two component gases (light-heavy)	Diffusion coefficient [cm²/s]
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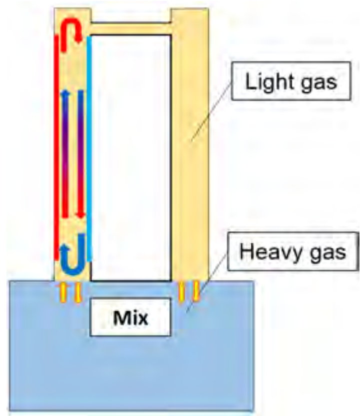
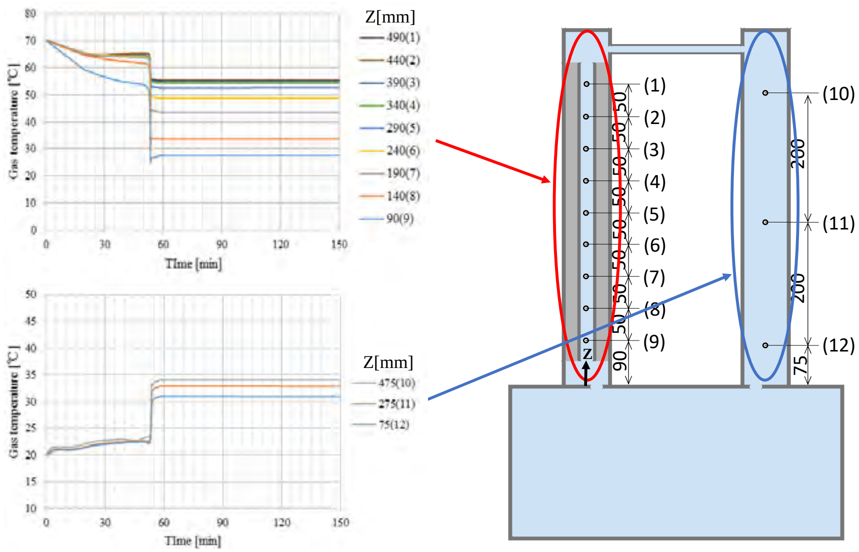
Temperature difference between wall [K]
30, 50, 70, 100

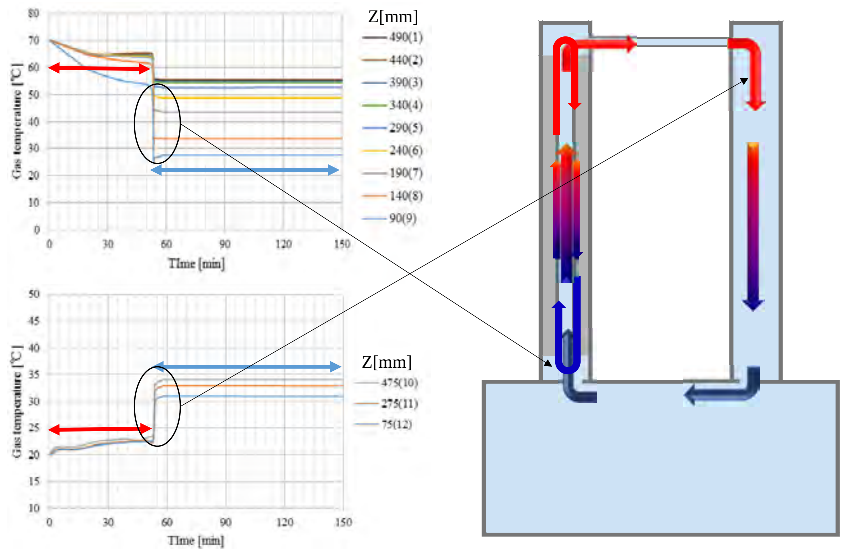


Numerical result (change of gas temperature)



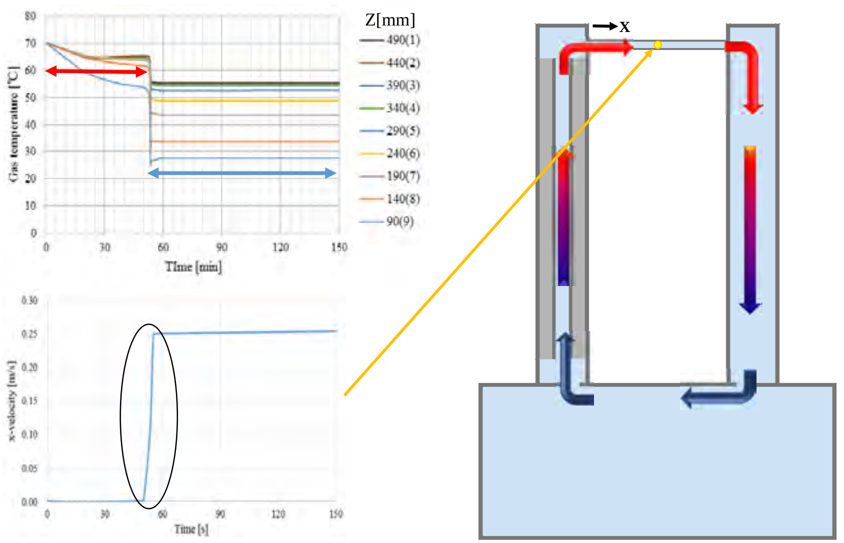
(He-Ar, ΔT=100K)

Numerical result (change of gas temperature)



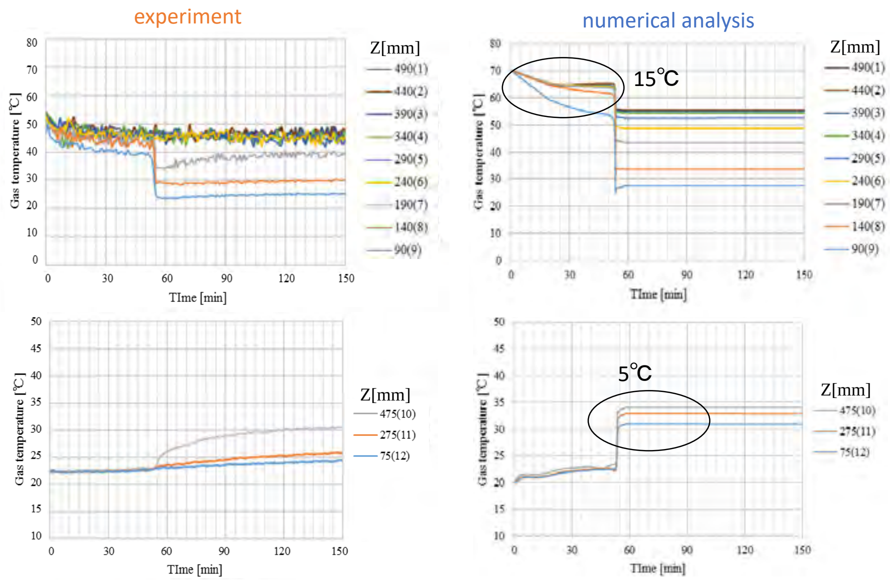
(He-Ar, ΔT=100K)

Numerical result (change of velocity)



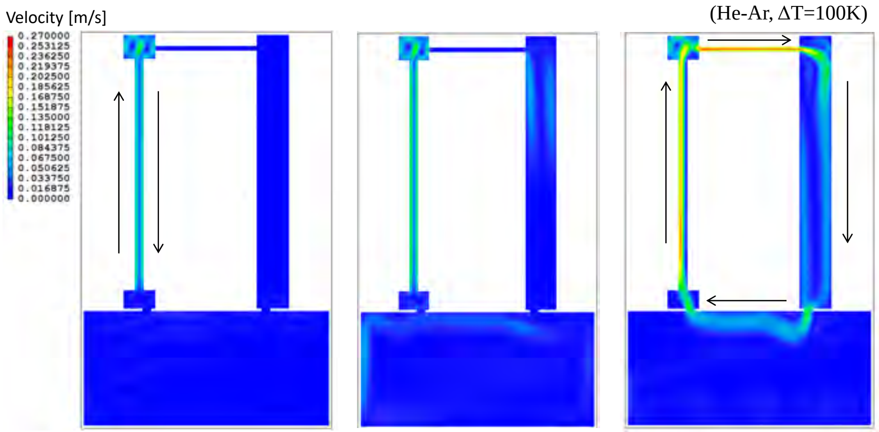
(He-Ar, ΔT=100K)

Comparison between experiment and numerical analysis



(He-Ar, ΔT=100K)

Numerical result (distribution of gas velocity)

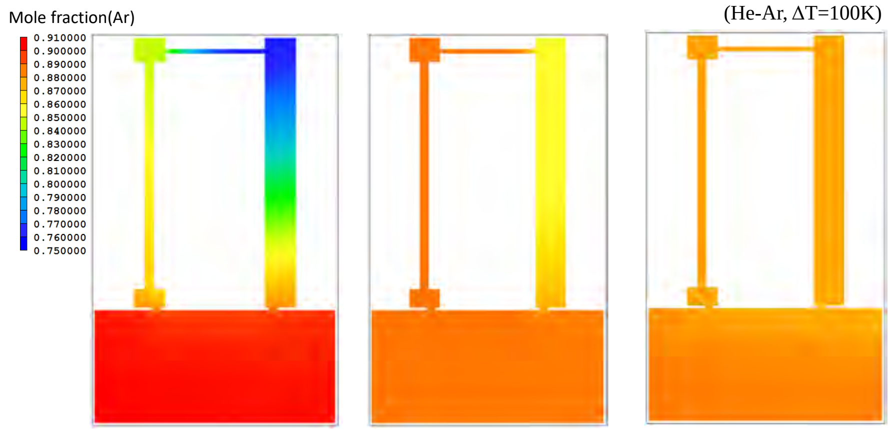


(a)30min — Localized natural convection generated in the left side slot.

(b)52min — Just before natural circulation generated.

(d)54min — Natural circulation generated through the passage.

Numerical result (distribution of mole fraction)



(a)30min — Mixing by molecular diffusion was promoted by the localized natural convection in the left side slot.

(b)52min — Just before natural circulation generated.

(d)54min — Natural circulation generated through the passage and mole fraction became uniform.

Comparison between experiment and numerical analysis Onset time of natural circulation

Experiment

ΔT [K]	He/Ar [min]	He/N_2 [min]	Ne/Ar [min]	N_2/Ar [min]
30	90	105	140	180
50	75	76	130	140
70	60	72	100	90
100	① 55	② 60	④ 85	③ 70

Numerical analysis

ΔT [K]	He/Ar [min]	He/N_2 [min]	Ne/Ar [min]	N_2/Ar [min]
30	84	103	128	164
50	76	80	115	130
70	65	77	109	97
100	① 52	② 63	④ 93	③ 76

Difference between experiment and numerical analysis

ΔT [K]	He/Ar [%]	He/N_2[%]	Ne/Ar [%]	N_2/Ar [%]
30	-6.67	-2.22	-8.33	-8.98
50	1.78	5.26	-11.5	-6.90
70	8.33	6.48	8.50	7.59
100	3.64	4.44	9.41	8.57

― : faster than experiment

Relationship between onset time of natural circulation and Gr number

Generation time（analysis）

ΔT [K]	He/Ar [min]	He/N_2 [min]	Ne/Ar [min]	N_2/Ar [min]
30	84	103	128	164
50	76	80	115	130
70	65	77	109	97
100	57	63	93	76

Gr number（in the left slot）

ΔT [K]	He/Ar（$\times 10^4$）	He/N_2 ($\times 10^4$)	Ne/Ar ($\times 10^4$)	N_2/Ar ($\times 10^4$)
30	0.045 ～ 0.95	0.055 ～ 0.84	0.44 ～ 2.1	2.7 ～ 3.2
50	0.068 ～ 1.4	0.076 ～ 1.3	0.75 ～ 2.7	4.1 ～ 5.0
70	0.079 ～ 1.7	0.090 ～ 1.5	0.84 ～ 2.9	4.8 ～ 6.0
100	0.10 ～ 2.2	0.11 ～ 1.8	1.2 ～ 4.4	6.8 ～ 11
Density ratio	1/10	1.4/10	7/10	5/10

- Onset time of natural circulation became short with increasing temperature difference.
- Gr number increases with increasing temperature difference.

Onset time of natural circulation became short because Gr number increased. Natural convection became strong and mixing of gases was promoted.

Relationship between onset time and diffusion coefficient

Generation time（analysis）

ΔT [K]	He/Ar [min]	He/N₂ [min]	Ne/Ar [min]	N₂/Ar [min]
30	① 84	② 103	③ 128	④ 164
50	① 76	② 80	③ 115	④ 130
70	① 65	② 77	④ 109	③ 97
100	① 57	② 63	④ 93	③ 76

Diffusion coefficient

ΔT [K]	He/Ar [cm/s²]	He/N₂ [cm/s²]	Ne/Ar [cm/s²]	N₂/Ar [cm/s²]
30	0.742	0.678	0.325	0.205
50	0.779	0.712	0.326	0.211
70	0.833	0.763	0.355	0.228
100	0.888	0.824	0.374	0.234

- When temperature difference was 30 and 50 K, onset time became short with increasing diffusion coefficient.
- Onset time of N_2/Ar and that of Ne/Ar were reversed at 70 and 100 K.

Relationship between onset time and diffusion coefficient

Generation time（analysis）

ΔT [K]	He/Ar [min]	He/N₂ [min]	Ne/Ar [min]	N₂/Ar [min]
30	① 84	② 103	③ 128	④ 164
50	① 76	② 80	③ 115	④ 130
70	① 65	② 77	④ 109	③ 97
100	① 57	② 63	④ 93	③ 76

	Gr number		Diffusion coefficient	
ΔT [K]	Ne/Ar (×10⁴)	N₂/Ar (×10⁴)	Ne/Ar [cm/s²]	N₂/Ar [cm/s²]
30	0.44 ～ 2.1	2.7 ～ 3.2	0.325	0.205
50	0.75 ～ 2.7	4.1 ～ 5.0	0.326	0.211
70	0.84 ～ 2.9	4.8 ～ 6.0	0.355	0.228
100	1.2 ～ 4.4	6.8 ～ 11	0.374	0.234

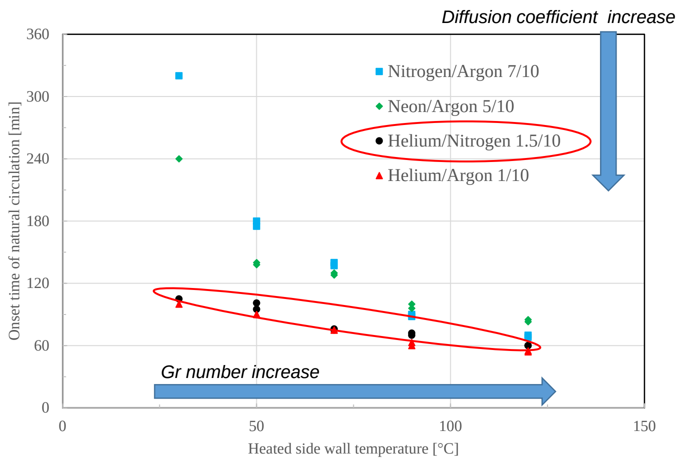
- When temperature difference was 30 and 50 K, onset time became short with increasing diffusion coefficient.
- Onset time of N_2/Ar and that of Ne/Ar were reversed at 70 and 100 K.

This is because Gr number of N_2/Ar was larger than that of Ne/Ar, so natural convection became strong.

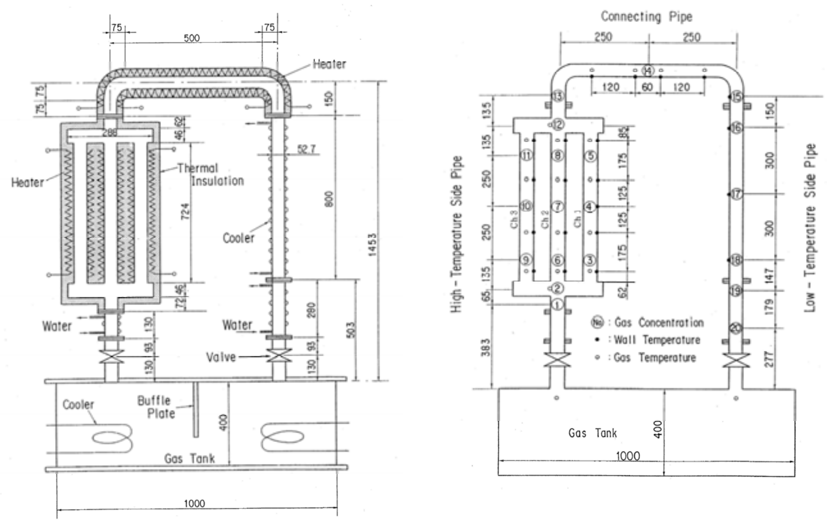
When temperature difference is small, onset time depended mainly on diffusion coefficient.
When temperature difference is large , onset time depended not only on diffusion coefficient but also on localized natural convection.

Influence that combination of two component mixed gas exerts on onset time of natural circulation

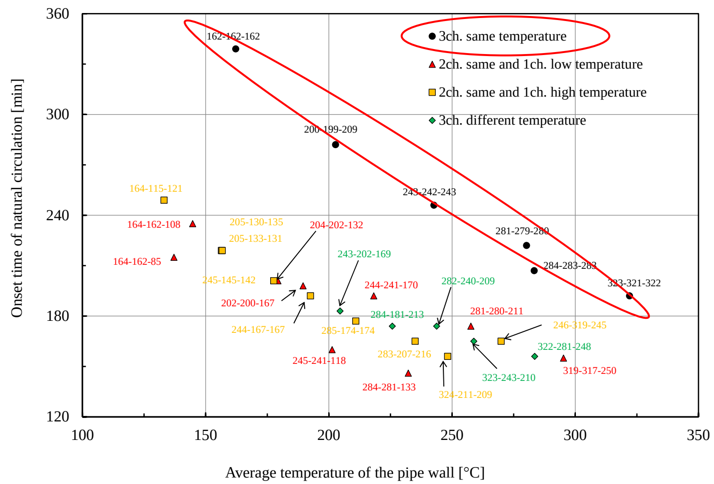
Figure shows the onset time of natural circulation against of the wall temperature of the high-temperature side passage.



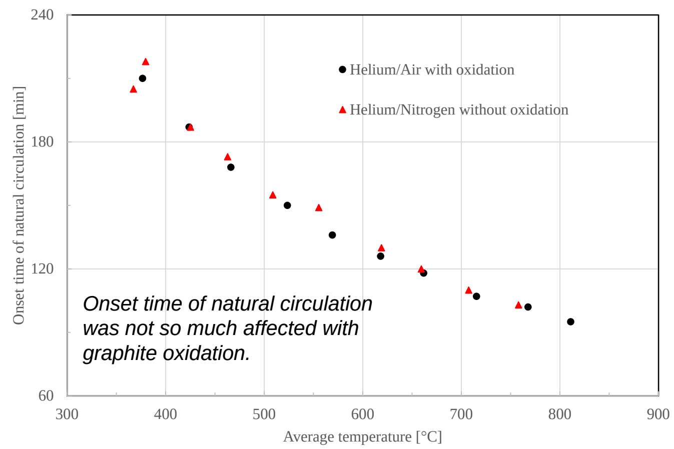
3 parallel vertical channels having different temperature



Influence that temperature difference of 3 parallel vertical channels exerts on onset time of natural circulation

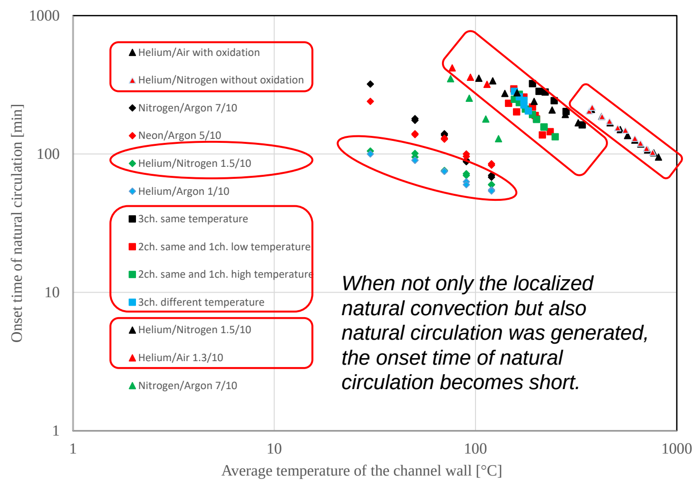


Influence that graphite oxidation on the reverse U-shaped vertical channel exerts on onset time of natural circulation



Onset time of natural circulation against wall temperature of the high-temperature side of the reverse U-shaped passages (height of heated part is less than 1m)

Figure shows the onset time of natural circulation obtained by 3 apparatus. Three apparatus are the reverse U-shaped tube, three parallel channels, and vertical parallel walls. The height of the heated part is less than 1m.



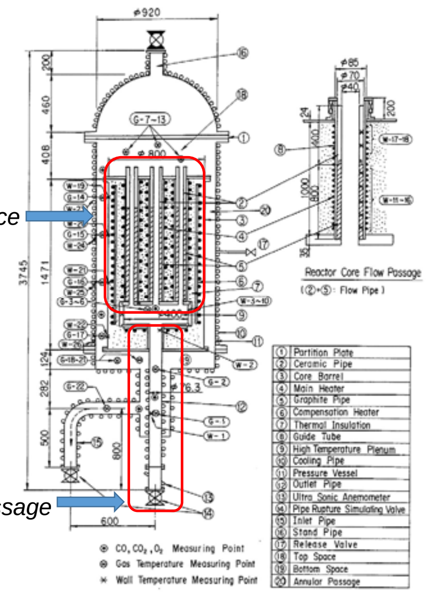
Experimental apparatus simulated HTTR

When natural circulation was generated, the onset time of natural circulation becomes short.

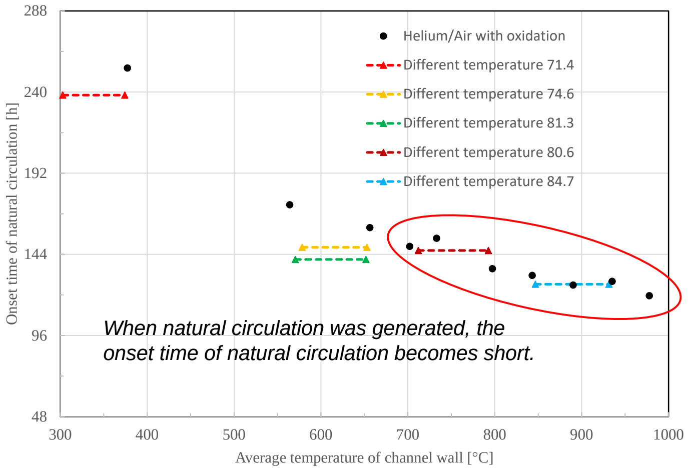
Temperature difference

The onset time of natural circulation becomes long when the phenomenon is governed mainly by molecular diffusion.

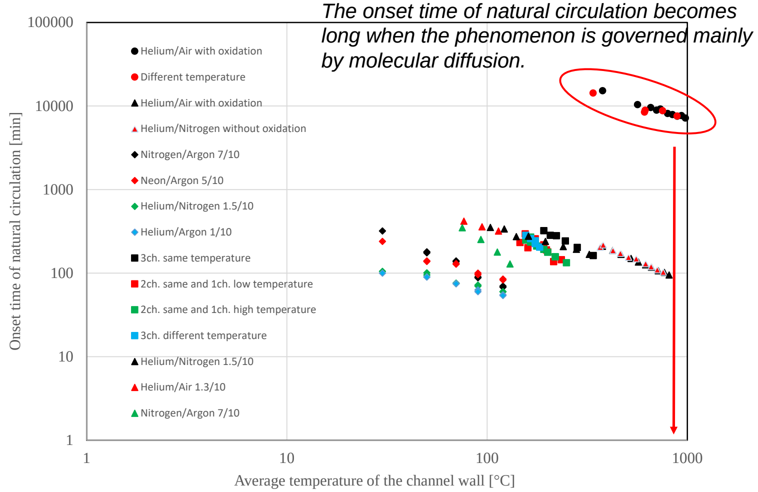
Length of vertical passage



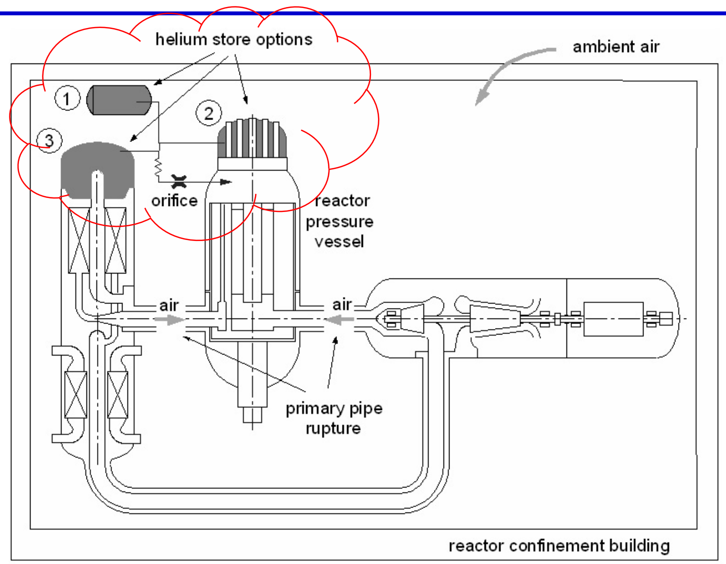
Influence that temperature difference in the vertical graphite passage exerts on onset time of natural circulation



Influence that vertical length of the passage under the core exerts on onset time of natural circulation



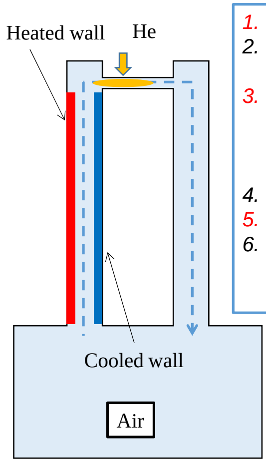
Proposed system in the case of GTHTR300 (JAEA's idea)



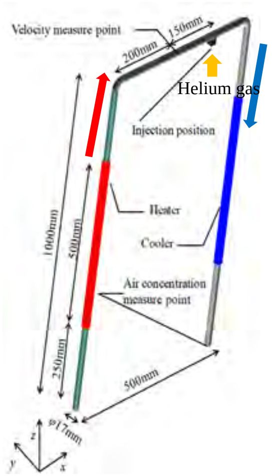
Ref. Yan, X. L. et al. (2008). "A study of air ingress and its prevention in HTGR, " Nucl. Technology, ***163, No.3****, pp.401-415.*

Experimental procedure (He injecting)

In order to investigate of preventing natural circulation flow by injecting helium gas, an experiment has been done as follows.

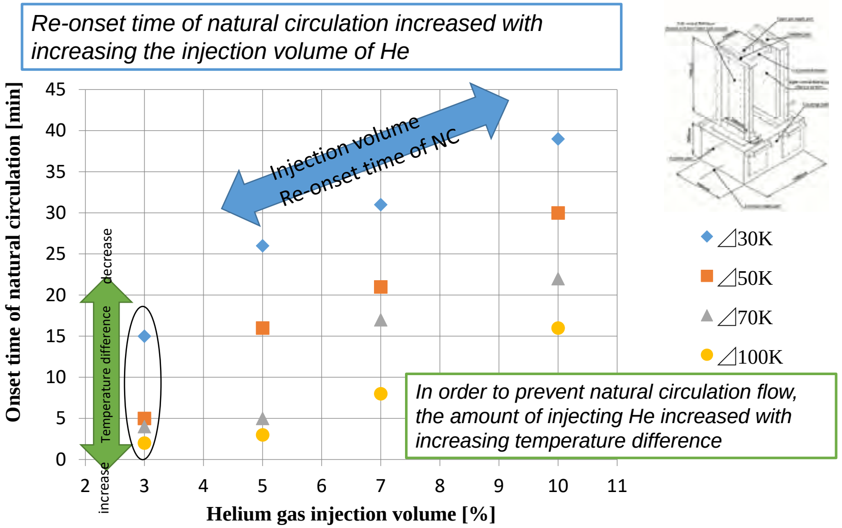


1. *Heavy gas is filled with apparatus.*
2. *Two vertical wall of the left hand side slot is heated and cooled.*
3. *Natural circulation flow are produced. When the steady state is established, helium gas injects from the top of the apparatus.*
4. *Experiment starts.*
5. *Natural circulation will be stopped.*
6. *After the time elapsed, natural circulation will be reproduced suddenly.*



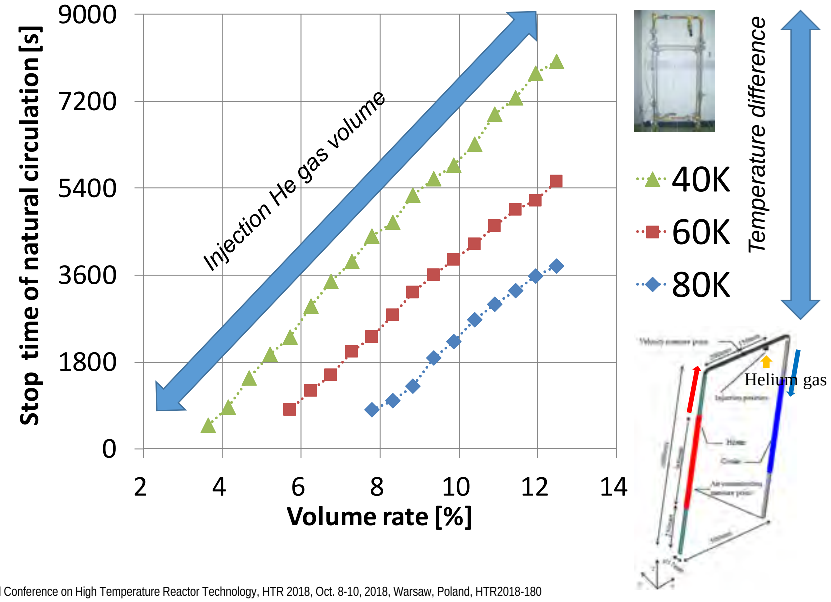
Experimental results regarding re-onset of NC

Re-onset time of natural circulation increased with increasing the injection volume of He



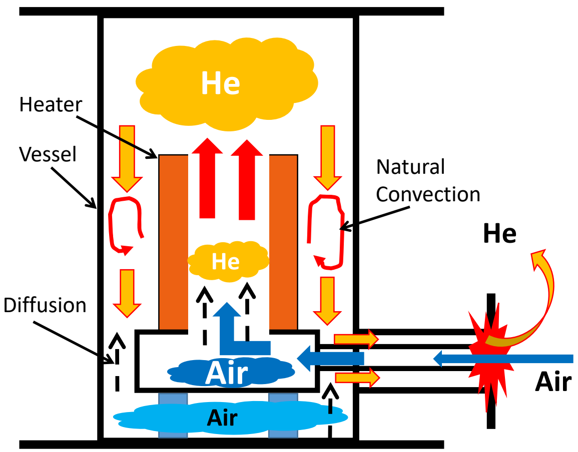
In order to prevent natural circulation flow, the amount of injecting He increased with increasing temperature difference

Relationship between elapsed time and injection volume



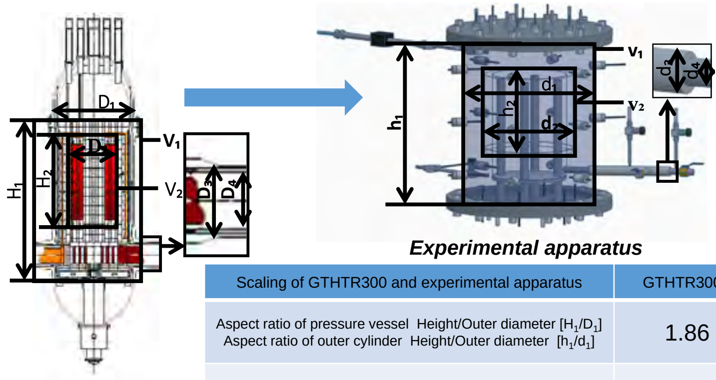
Air Ingress Scenario in the case of the horizontal pipe break

- After the pipe ruptures, air will flow into the bottom part of the RPV by the counter-current flow.
- The density stratified fluid layer will be formed.
- Buoyancy force will produce between the hot and cold legs.



- *As the buoyancy force will be small, the natural circulation flow will not produce under the condition of this density distribution.*
- *Thus, air will transport to the core by mainly molecular diffusion.*
- *If the localized natural convection occur inside the channel, it is difficult to estimate not only the density change of gas mixture but also the onset time of natural circulation through the reactor.*
- *After the time elapses, the natural circulation may occur suddenly.*

Experimental apparatus simulating GTHTR300 series

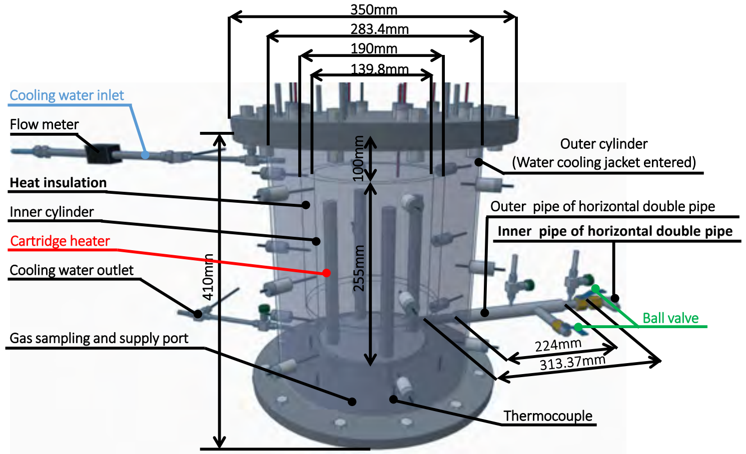


Sectional view of GTHTR300

Experimental apparatus

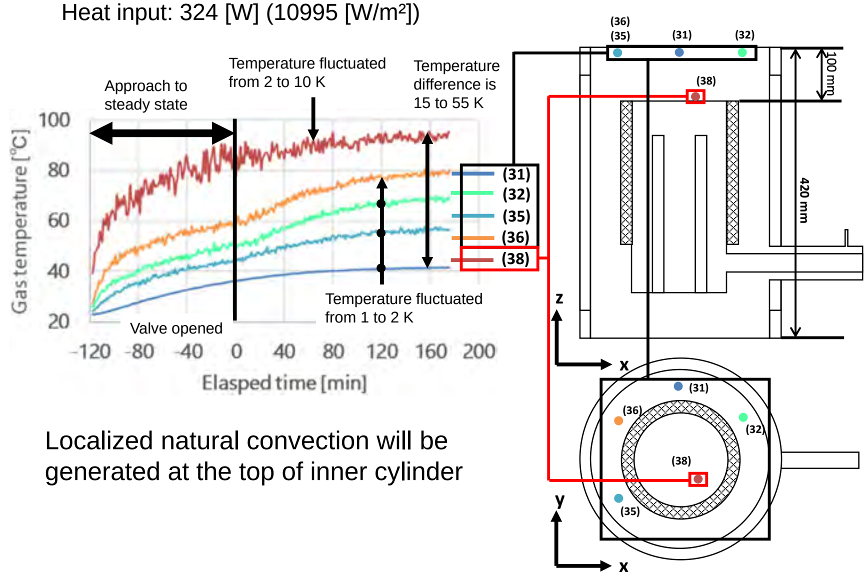
Scaling of GTHTR300 and experimental apparatus	GTHTR300/Apparatus
Aspect ratio of pressure vessel Height/Outer diameter [H_1/D_1] Aspect ratio of outer cylinder Height/Outer diameter [h_1/d_1]	1.86 / 1.53
Aspect ratio of core Height/Outer diameter [H_2/D_2] Aspect ratio of Inner cylinder Height/Outer diameter [h_2/d_2]	1.50 / 1.43
Diameter ratio of primary double coaxial pipe [D_3/D_4] Diameter ratio of horizontal double coaxial pipe [d_3/d_4]	1.30 / 1.50
Volume ratio of pressure vessel & core [V_1/V_2] Volume ratio of outer cylinder & inner cylinder [v_1/v_2]	5.00 / 4.60

Experimental apparatus



Results of temperature profiles in the apparatus

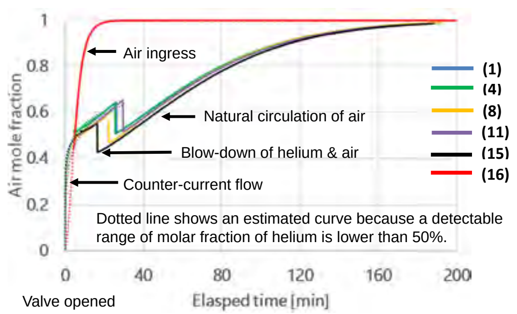
Heat input: 324 [W] (10995 [W/m²])

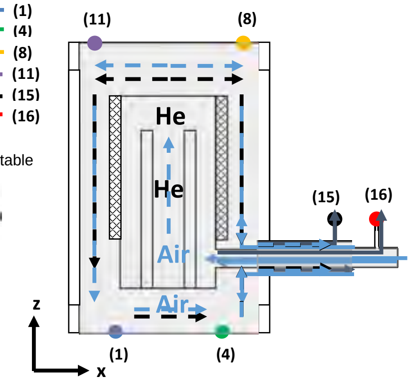


Localized natural convection will be generated at the top of inner cylinder

Results of molar fraction change in the apparatus

Heat input: 324 [W] (10995 [W/m²])





Blow-down of helium gas by a counter-current flow.

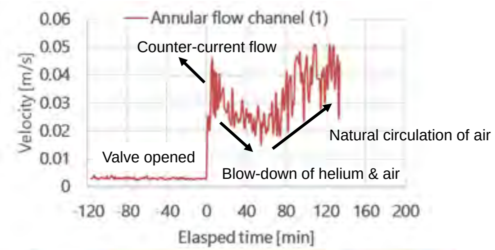
Blow-down of helium gas that exists under the broken part of the pipe.

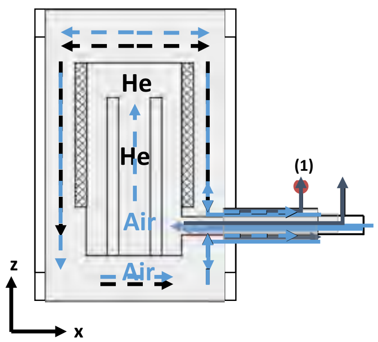
Blow-down of helium and air. (mixture gas)

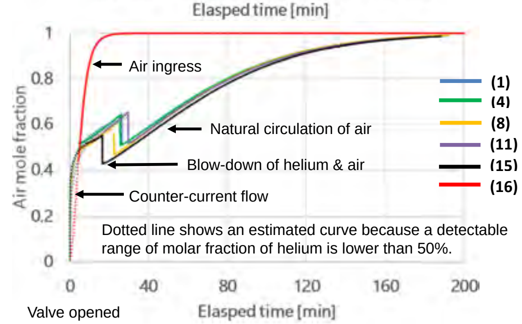
Onset of natural circulation of air.

Results of inlet velocity change at the horizontal pipe

Heat input: 324 [W] (10995 [W/m²])







Blow-down of helium gas by a counter-current flow.

Blow-down of helium gas that exists under the broken part of the pipe.

Blow-down of helium and air. (mixture gas)

Onset of natural circulation of air.

Conclusion

- *The onset time of the natural circulation depended more on molecular diffusion than the strength of localized natural convection when the temperature difference was small.*
- *On the other hand, the onset time of natural circulation depended not only on molecular diffusion but also on localized natural convection when the temperature difference between two vertical walls was large.*
- *These flow characteristics will be the same as those of phenomena generated in the passage between a permanent reflector and a pressure vessel wall of the GTHTR-300C.*
- *In order to prevent a large amount of air ingress into the reactor by injecting helium gas, we are planning to analyze the method for preventing air ingress by helium canister during a depressurization accident in the GTHTR-300C system.*
- *In addition, we are now doing the experiment by the double coaxial cylindrical apparatus and also are planning to carry out 3-D numerical analysis of air ingress when the horizontal primary pipe ruptured.*