Water Cleaning System for the Exhaust Pipe of HLW Glass Melter (LFCM) － 17180

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ABSTRACT

Vitrification technology has been generally applied to stabilize High-Level Radioactive Waste (HLW) generated from spent fuel reprocessing. In Japan, Joule Heated Liquid Fed Ceramic Melter (LFCM) system is selected for HLW vitrification and the recent active test has been successfully demonstrated its stable operation.

The higher reliability of off-gas treatment system (OGTS) which consists of wet scrubber, absorbers and filters connected to the LFCM is also important to ensure long term system operation. The OGTS removes radioactive gases, mists and dust generated by LFCM and maintains radioactive containments by keeping negative pressure inside. In the past active and inactive tests, it was observed that differential pressure in the exhaust pipe attached to LFCM gradually increased during continuous operation and some deposits were observed inside the off-gas pipe. So the cleaning operation needs to be improved and more frequent in order to avoid the exhaust pipe clogging.

Therefore we investigated several cleaning systems and operational methods for the exhaust pipe of LFCM. As a result, we have successfully developed the modified water cleaning system*. In this presentation we will introduce our water cleaning system. In addition, we will present the result of inactive mock-up tests for the visualization of this water cleaning system.

INTRODUCTION

High temperature operation of LFCM generates various hazardous elements including substantial dust. In general, the wet scrubbing process is installed to the upstream of OGTS for LFCM in order to remove volatile ruthenium, cesium and other mists and dust. The Process flow of OGTS for LFCM is shown in Fig. 1.

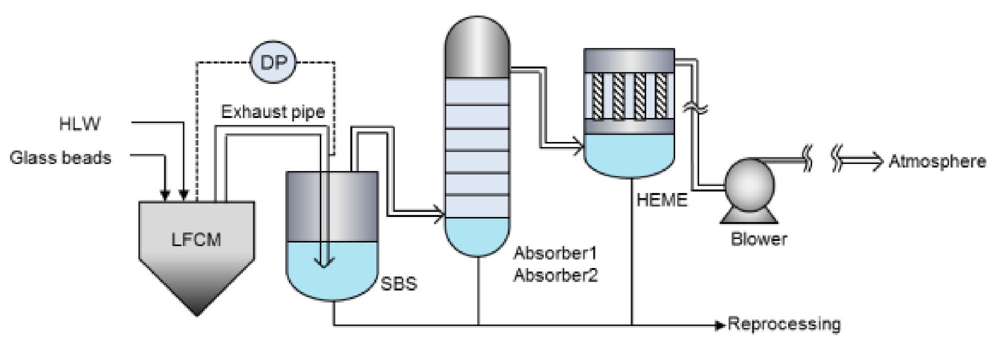


Fig. 1 Process Flow of OGTS for LFCM

*: Water cleaning system is the operating method that removes the deposition of dust of the inside surface of the exhaust pipe using water.

It is well-known that dust deposits at the off-gas outlet of the furnaces in many kind of industries. Also clogging in the exhaust pipes has been experienced since the early days of LFCM development. Therefore we investigated several cleaning systems to prevent deposition of dust in the exhaust pipes.

In this paper, we will introduce our main results of investigation from the early days to the latest.

STRUCTURE OF THE EXHAUST PIPE AND ACCESSORIES

The structure of the exhaust pipe and accessories is shown in Fig. 2.

LFCM and SBS are connected by the exhaust pipe. We calculate the clogging level of the inside of the exhaust pipe by measuring differential pressure between LFCM and the exhaust pipe during LFCM operation. On the location of the differential pressure gage is shown in Fig.2. In this paper, we use the following terms for each section of the exhaust pipe.

Section 1: outlet of LFCM

Section 2: vertical section

Section 3: first bend section

Section 4: between Section 3 and Section 5

Section 5: second bend section

Section 6: falling gradient section

Section 7: third bend section

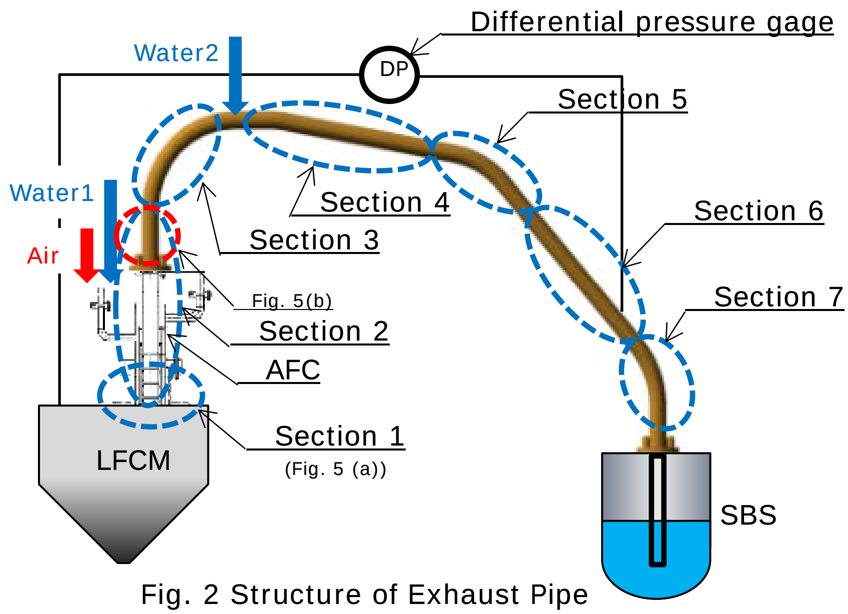


Fig. 2 Structure of Exhaust Pipe

CLOGGING LEVEL OF THE EXHAUST PIPE AND THE COUNTERMEASURE

Installation of Air Film Cooler (AFC) on the Outlet of LFCM

We have experienced problems that increase differential pressure of the exhaust pipe caused by dust since the early days of operation, and many kind of furnace had the same problems in other industries.

We observed the inside surface of the exhaust pipe after LFCM operation. As the result, we found the cause of increasing differential pressure. It was due to deposition of dust, which is generated by LFCM, at the outlet of LFCM.

Therefore we installed the AFC on the outlet of LFCM to prevent deposition of dust.

The detail structure of AFC is shown in Fig. 3.

AFC is a triple pipe which has some slits for supplying hot air to the inner pipe.

The off-gas generated by LFCM flows in the inner pipe. (Green arrow)

And we supply hot air* to the inner pipe from the slits of the middle pipe and the slit of the outer pipe so that hot air forms laminar flow on inside surface of exhaust pipe to prevent deposition of dust.

We checked Section 1 and Section 2 after LFCM operation. As a result, we found that AFC is effective to decrease deposition of dust at Section 1 but is not effective to decrease deposition of dust at the downstream of AFC.

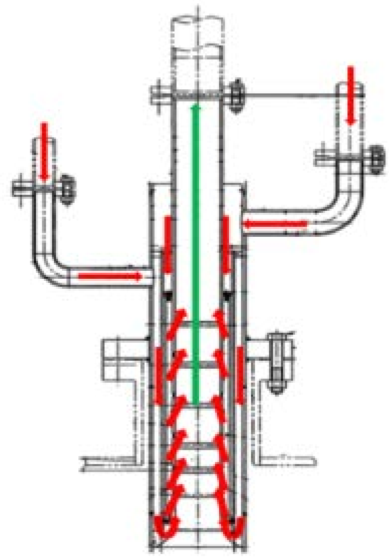


Fig. 3 Detail Structure of AFC

Water Cleaning System

Theory of Water Cleaning System

We studied the water cleaning system using the flooding phenomenon. According to G. F. Hewitt's research, the theory of flooding phenomenon is shown below:

> In plug flow, a falling film exists around the plug flow bubble. Such falling films can exist only if the gas velocity over them is relatively small. In annular flow, on the other hand, there exists a climbing film; climbing films can exist only if the gas velocity over them is sufficiently high. The transition between these two extreme cases is illustrated in Fig. 4. As the gas flow is increased, the system passes from one of falling liquid film flow (a) through the "flooding" transition at which liquid begins to travel upward (b), to simultaneous upward and downward liquid flow (c and d), to climbing film flow (e). When the gas flow is reduced, a point is reached at which liquid begins to creep below the injection point, and this is termed "flow reversal."[1]

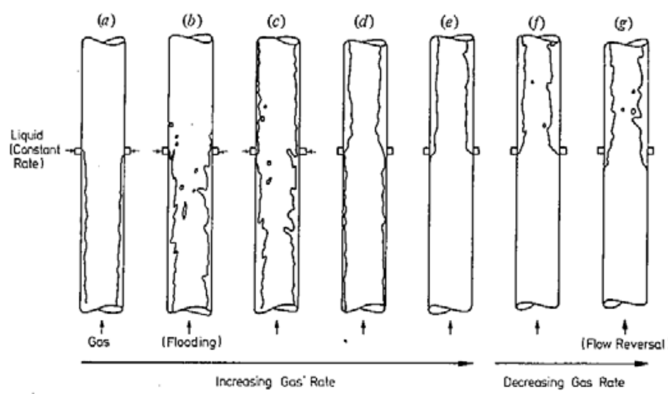


Fig. 4 Flooding Phenomenon[1]

*: We supply hot air to avoid condensation.

Summary of Water Cleaning System

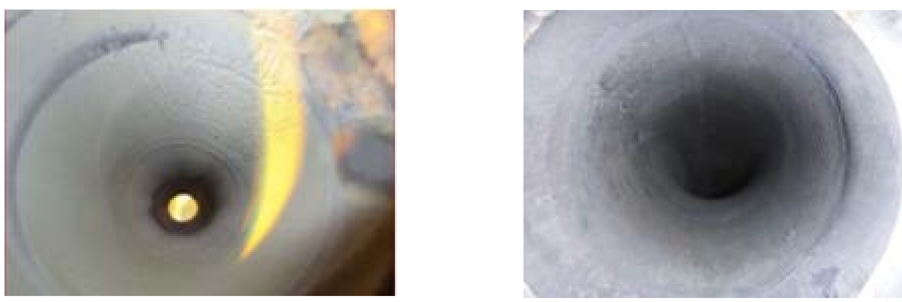
The concept of water cleaning system is shown in Fig. 2. The water cleaning system can be used while the LFCM feeding operation is running. The operational sequence is the following:

a. Set the off-gas flow rate at Section 1 to generate the flooding phenomenon.
b. Supply water1[1] to inner pipe at Section 1 through the AFC. The area of Section 1 and 2 are cleaned by flooding phenomenon.
c. Add water2[2] to the inlet of the exhaust pipe. The area of Section 4 to 7 is cleaned by water2.
d. After that, stop to supply water1 and 2 simultaneously.

Performance Test of Water Cleaning System

We carried out a full-scale performance test of water cleaning system in LFCM. The pictures of Section 1 and downstream of AFC in Section 2 after LFCM operation are shown in Fig. 5.

Fig. 5 shows that the dramatic performance of the water cleaning system is clearly visible. Therefore we adopted the water cleaning system on OGTS for HALW Vitrification Facility (HVF).



(a) View of Section 1 (b) View of Downstream of AFC in Section 2

Fig. 5 Condition of Exhaust Pipe After LFCM Operation Using Water Cleaning

Operating Result of HVF

During the HVF operation, we carried out water cleaning when the differential pressure increased. For quite a while the water cleaning decreased the differential pressure close to the initial amount. But the performance of water cleaning dropped with the passage of operational time so we had to carry out water cleaning in shorter intervals. Also we found that differential pressure increased slowly and continuously after each water cleaning operation.

We examined the condition of the exhaust pipe after LFCM operation in Rokkasho Vitrification Laboratory (RVL)[3] to clarify the cause of the above-mentioned problem. In RVL, developmental tests have been carried out using the same water cleaning system as in HVF.

The different conditions of the exhaust pipe after LFCM operation are shown in Fig.6.

1: See the Fig. 2 and Fig. 3.
2: See the Fig. 2.
3: RVL which is owned by Japan Nuclear Fuel Ltd. (JNFL) is a research and development facility that simulates High Active Liquid Waste (HALW) Vitrification Facility (HVF).

We observed that Section 1 and Section 2 remained clean but substantial amounts of dust deposited at Section 3 and at the thermo-well in Section 5, they are shown in Fig. 6.

Therefore we concluded that the present water cleaning system is effective to prevent deposition of dust at Section 1 and Section 2 but is not effective enough to prevent deposition of dust at Section 3 to 7.

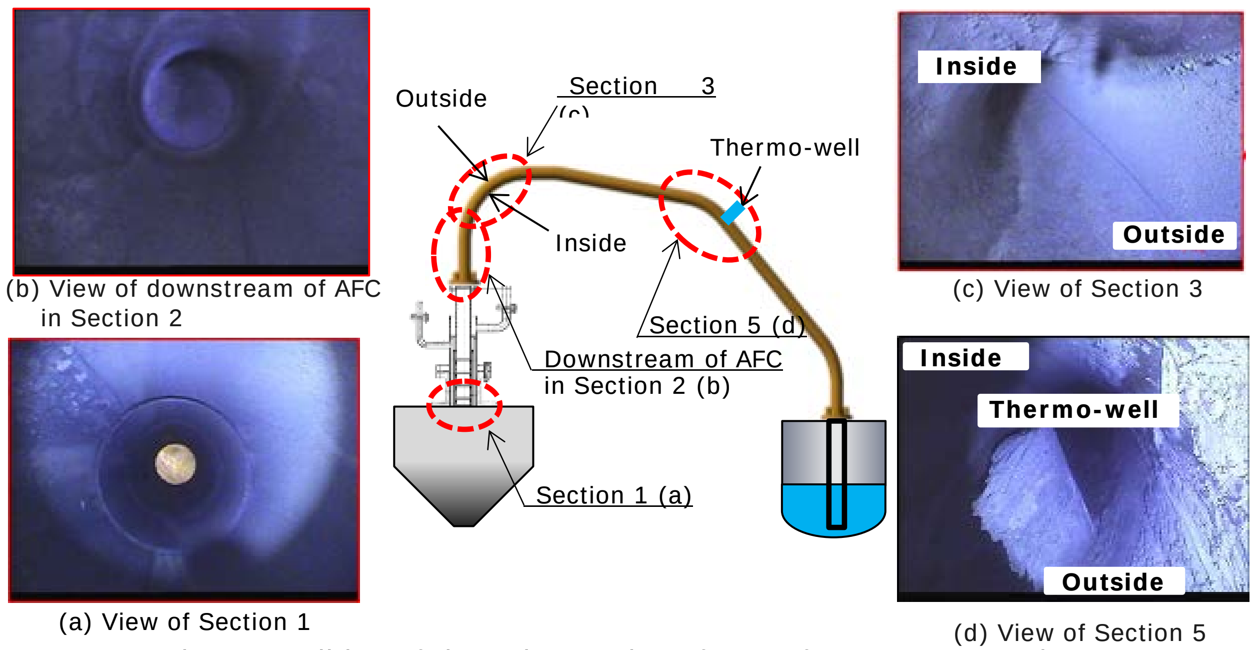


Fig. 6 Condition of the Exhaust pipe of RVL After LFCM Operation

MOCK-UP TEST OF ADVANCED WATER CLEANING SYSTEM

We carried out a Mock-up test of advanced water cleaning system to solve the problem above. In this chapter, we will introduce the latest results of the inactive Mock-up test.

Test Equipment

We carried out the mock-up test of advanced water cleaning system at RVL which has the same scale and systems of OGTS as HVF. We have utilized the part of OGTS in RVL because we had to simulate some operating conditions of HVF. The simulated operating conditions of HVF are shown in the followings:

- Structure and layout of AFC, exhaust pipe and accessories
- The off-gas velocity in the exhaust pipe
- The flow rate of water1 and water2

We substituted the LFCM with a temporary vessel and the exhaust pipe with a transparent acrylic pipe in order to visualize the situation. All the other parts remained the same as shown in Fig. 7.

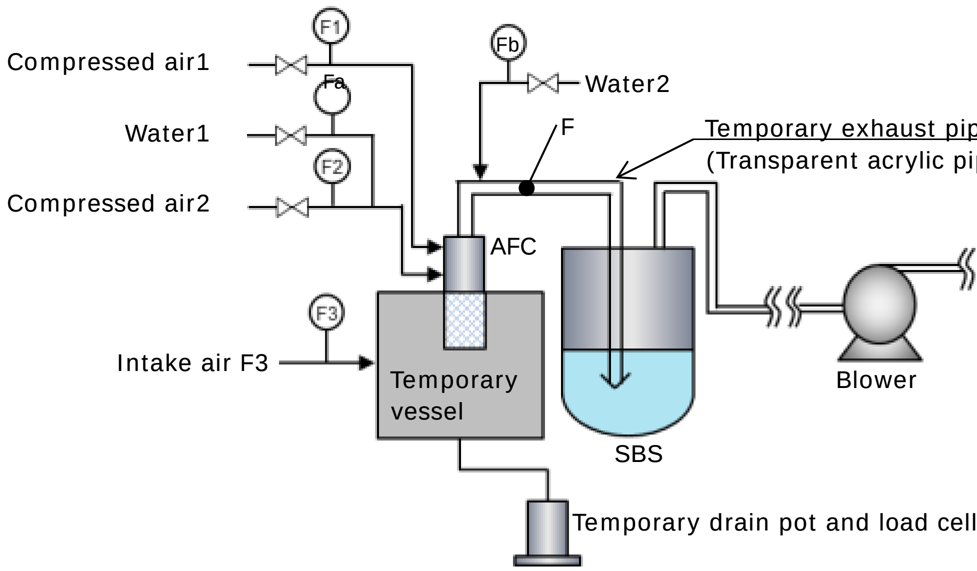


Fig. 7 Mock-up Test Equipment

Test Parameters

The water cleaning system removes the deposition of dust from inside the surface of the exhaust pipe using only water. Section 1 and Section 2 is cleaned by the Flooding phenomenon which is using a two phase flow of gas and water. Section 3 to 7 is cleaned by using only the two phase flow of gas and water. Therefore the off-gas velocity, the feed flow rate of water1 and water2 and the position of feeding water inlet on the exhaust pipe are exceedingly important elements in the water cleaning system. So we selected these elements for this mock-up test as parameters.

- Off-gas velocity
- Feed flow rate of water1 and 2
- Position of feeding water inlet on the exhaust pipe（See Fig. 8）

The position Ⅰ was located at the same position as HVF. We added Positions Ⅱ to Ⅳ as the test parameters in order to improve the performance of the water cleaning system.

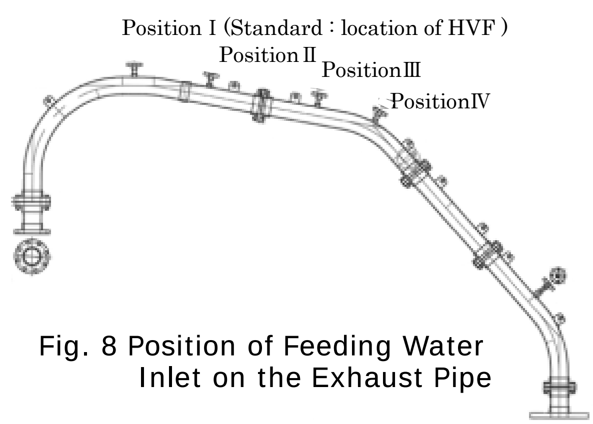


Fig. 8 Position of Feeding Water Inlet on the Exhaust Pipe

Test Procedure

Test procedure is as follows:

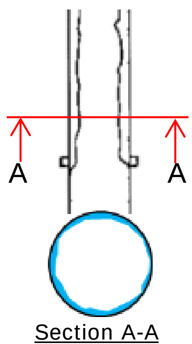
- Set the off-gas velocity to test condition F by adjusting F1, F2 and F3, as shown in Fig. 7.
- Supply water1 to inner pipe at Section 1 through the AFC
- Check the condition of the two phase flow of air and water in Section 1 and 2
- Add water2 to the inlet of exhaust pipe
- Check the condition of two phase flow of air and water in Section 3 to 7

Evaluation Method

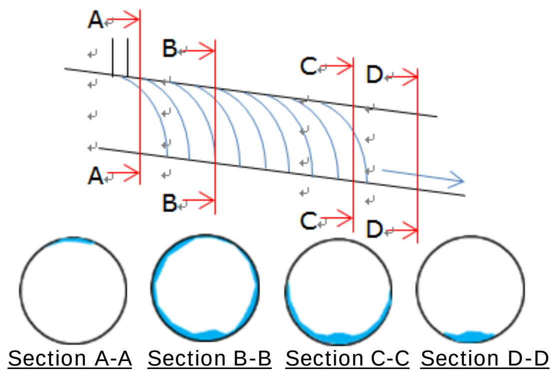
The purpose of water cleaning operation is to remove the deposition of dust from the inside surface of the exhaust pipe. The cleaning water flow is shown in Fig. 9.

Concerning 'Section 1 and 2', almost all the cleaning water goes up as 'wet-wall flow' (annular flow) shown in Fig. 9(a) by flooding phenomenon. Therefore an around 100% cleaning effect of these sections can be expected.

But the downstream of water2 at the supply nozzle is not a ‘wet-wall flow’. The cleaning water flows from the upper part to the down part of the pipe as a parabolic flow shown in Fig. 9(b). It can be seen that the water flows only top of the pipe at section A-A and the water flow becomes an intermittent ‘wet-wall flow’ in section B-B. Therefore the cleaning effect of these areas can be expected here. In section C-C and section D-D only the bottom part of the pipe can be cleaned. We evaluated the cleaning effect by measuring section B-B and the size of wet area in the other sections. We called the wet-wall, the 'Wetted area' and evaluated the cleaning effect by the size of this area.



(a)Flow condition at vertical section



(b)Flow condition at downstream of water2 at the supply nozzle

Fig. 9 The Cleaning Water Flow

The Sequence

The sequence of the mock-up test is the following:

STEP 1: Observation of the cleaning effect in the standard condition
STEP 2: Changing the off-gas velocity
STEP 3: Changing the cleaning water flow rate
STEP 4: Selection of the best cleaning effect based on STEP 1-STEP 3
STEP 5: Changing the position of water2 inlet
STEP 6: Selection of the best cleaning effect based on STEP 1-STEP 5

In STEP 1, we observed the cleaning effect of the normal water cleaning operation in HVF. It's well known that the off-gas velocity is important in the water cleaning system, but is not measured in HVF. So, we estimated the actual off-gas velocity from the known operational condition, which is the air flow rate supplied to LFCM and AFC, the HLW flow rate treated in LFCM and the measured temperature in thermo-well in Section 5. As a result of the estimation, we determined that the off-gas velocity in the standard condition is approximately 20m/s.

In STEP 2 and STEP 3, we investigated the cleaning effect while we changed the off-gas velocity and the cleaning water flow rate in order to heighten the cleaning effect.

In STEP 4, we selected the best cleaning effect in HVF based on the results of STEP 1-3.

In STEP 5, we investigated the cleaning effect while changing the position of water2 inlet which was a relatively simple improvement.

In STEP 6, we selected the best cleaning effect, based on the results of STEP 1-5.

Mock-up Test results

Observation of the Cleaning Effect in the Standard Condition (STEP 1)

We observed the cleaning effect in the standard condition of the water cleaning system in STEP 1. The standard condition is the same as in the normal operation of HVF. The cleaning effect in STEP 1 is shown in TABLE Ⅴ. We checked the size of 'wetted area' in the standard condition as shown in TABLE Ⅴ-Case S.

Changing the Off-gas Velocity (STEP 2)

We checked the cleaning effect while changing the off-gas velocity in STEP 2. The test parameters of the off-gas velocity is shown in TABLE Ⅰ. The other parameters are the same as in the standard condition. And the cleaning effect is shown in TABLE Ⅴ.

TABLE Ⅰ Test Parameters of the Off-gas Velocity (STEP 2)

Case			A	S	B
Flow rate of cleaning water	**Water1**	**L/h**	Standard		
	Water2	**L/h**	Standard		
Off-gas velocity (approximately)		**m/s**	15.0	20.0	23.0

The main comparison results of the cleaning effect in STEP 2 with Case S (STEP 1) are shown below and in TABLE Ⅱ.

① Case A=Off-gas velocity<Case S
- The 'Wetted area' in Section 3 increased, but in Section 4 decreased. (See TABLE Ⅴ-Case A)
- The amount of the drain water in the temporary drain pot increased.

② Case B=Off-gas velocity>Case S
- The 'Wetted area' in Section 3 decreased, but in Section 4 increased. (See TABLE Ⅴ-Case B)
- The amount of the drain water in the temporary drain pot decreased.

We found the above-mentioned comparison results in STEP 2. Case A may have an influence on the stable operation of LFCM because the amount of the drain water increased. Therefore we evaluated that Case B is better in STEP 2.

TABLE Ⅱ The Comparison Results With Case S (STEP 2)*

Case		A	B
Category	**Section 1-3**	○	△
	Section 4	△	○
	Amount of drain water	×	○
Evaluation		×	○

* ○: Good, △: Average, ×: Poor, －: Unchecked

Changing the Cleaning Water Flow Rate (STEP 3)

We checked the cleaning effect while changing the cleaning water flow rate in STEP 3 as shown in TABLE Ⅲ and the cleaning effect in TABLE Ⅴ. The other parameters are the same as in the standard condition.

TABLE Ⅲ Test Parameters the Cleaning Water Flow Rate (STEP 3)

Case			1	2
Flow rate of cleaning water	**Water1**	**L/h**	1.4S	Standard
	Water2	**L/h**	0	1.5S
Off-gas velocity (approximately)		**m/s**	20.0	20.0

(1) Water1 flow rate increased

Concerning the cleaning effect while changing water1 flow rate, the main comparison results with Case S (STEP 1) are shown below and in TABLE Ⅳ.

① Case 1=water1 flow rate＞Case S

- The 'Wetted area' in Section 1-3 increased. (See TABLE Ⅴ-Case1)
- The amount of the drain water in the temporary drain pot increased. But we estimated that the increase of the drain water does not influence the stable operation of LFCM in this case because the ratio to the amount of water1 supplied decreased.

(2) Water2 flow rate increased

Concerning the cleaning effect while changing water2 flow rate, the main comparison results with Case S (STEP 1) are shown below and in TABLE Ⅳ.

① Case 2=water2 flow rate＞Case S

- The 'Wetted area' in Section 4 increased. (See TABLE Ⅴ-Case 2)

In both case the Wetted area' increased so they are favored to the standard case.

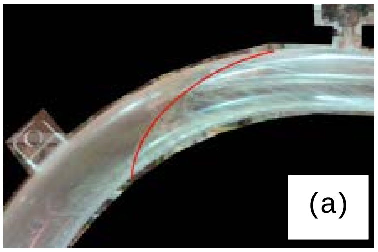
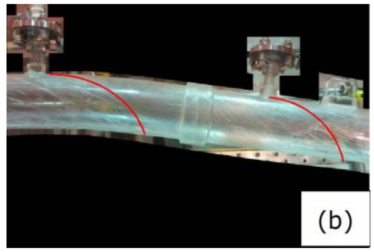
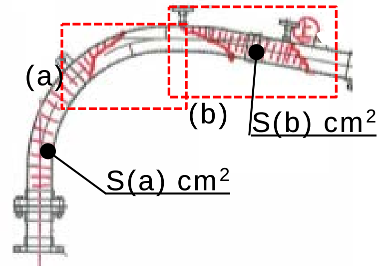
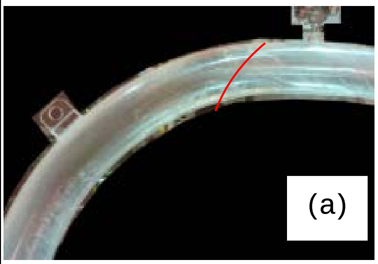
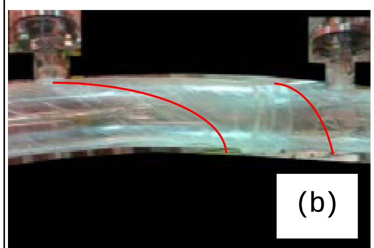
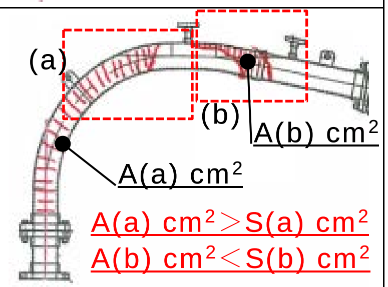
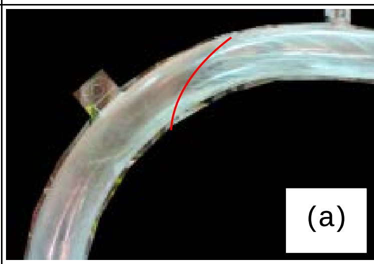
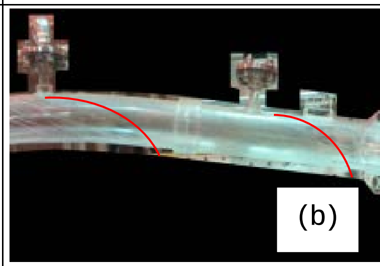
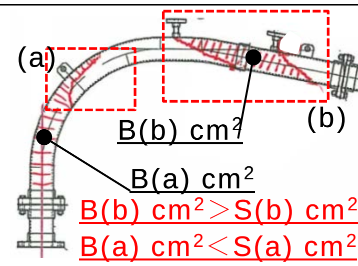
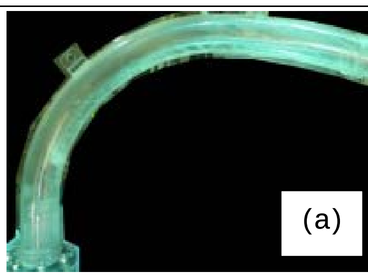
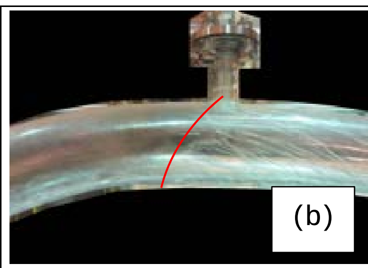
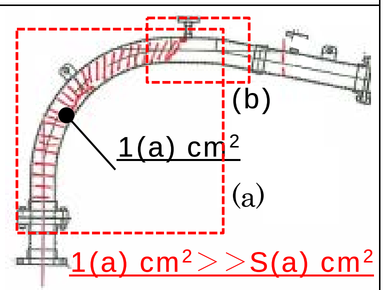
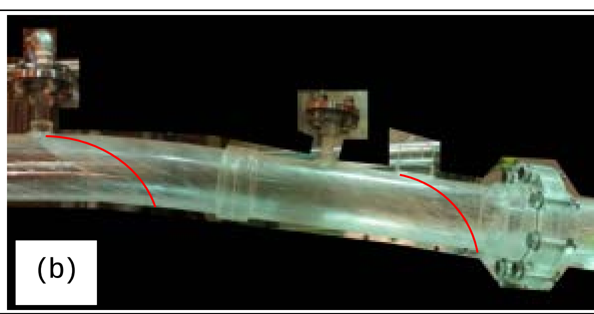
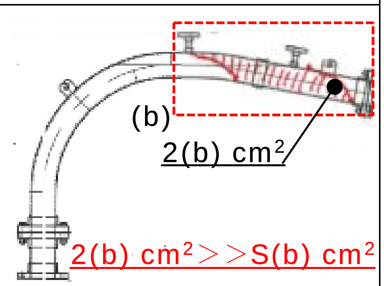
TABLE Ⅳ The Comparison Results With Case S (STEP 3) [1]

Case		1	2
Category	**Section 1-3**	○	—
	Section 4	—	○
	Amount of drain water [2]	○	—
Evaluation		○	○

1 ○: Good, △: Average, ×: Poor, －: Unchecked

2 This is evaluated by the ratio to the amount of water1 supplied.

TABLE Ⅴ The cleaning effect in STEP 1-3

Case	Section 3	Section 4	Sketch
S (Standard)			
A			
B			
	Section 1-3		
1			
	Section 4		
2			

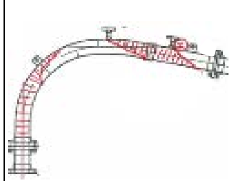
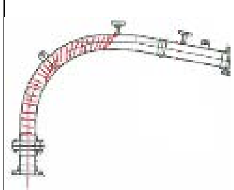
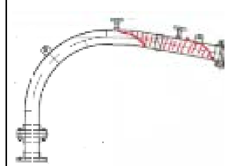
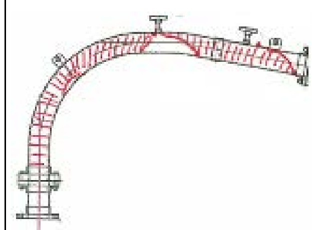
Selection of the Best Cleaning Effect in STEP 1-STEP 3 (STEP 4)

The comparison results in STEP 1-STEP 3 are shown in TABLE Ⅵ. We found the following tendency in there.

- As off-gas velocity increases, the 'Wetted area' in Section 4 increases and the amount of the drain water in the temporary drain pot decreases. (Case B)
- As water1 flow rate increases, the 'Wetted area' in Section 1-3 increases too. (Case 1)
- As water2 flow rate increases, the 'Wetted area' in Section 4 by increases as well. (Case 2)

So, we concluded that a combination of the above-mentioned item will provide the best cleaning effect in the existing equipment. The assumed the 'Wetted area' in this case is shown in TABLE Ⅵ as 'Combination①'.

TABLE Ⅵ The Comparison Results With Case S (STEP 1-3) *

Case	B	1	2	Combination①
Sketch				
Section 1-3	△	○	—	○
Section 4	○	—	○	○
Amount of drain water	○	○	—	○

* ○: Good, △: Average, ×: Poor, —: Unchecked

Changing the Position of water2 Inlet (STEP 5)

We checked the cleaning effect while changing the position of water2 inlet in order to heighten the cleaning effect of Section 4-6 with simple improvement of the exhaust pipe relatively. The position of water2 inlet on exhaust pipe is shown in Fig. 8. The test parameters are shown in TABLE Ⅶ. Flow rate of water2 is the standard condition. The cleaning effect of STEP 5 is shown in TABLE Ⅸ.

Concerning the cleaning effect of STEP 5, the main observational results are shown below and in TABLE Ⅷ.

TABLE Ⅶ Test Parameters Changing the Position of Water2 Inlet (STEP 5)

Case			Ⅰ (= S)	Ⅱ	Ⅲ	Ⅳ
Flow rate of cleaning water	**Water1**	**L/h**	0			
	Water2	**L/h**	Standard			
Off-gas velocity (approximately)		**m/s**	20.0			

① Case Ⅰ(Position Ⅰ)

This case is the same as in the Case S. We couldn’t see the ’Wetted area’ in Section 5. Therefore the cleaning effect can’t be expected in Section 5 without bottom of pipe. (See TABLE Ⅸ-Ⅰ)

② Case Ⅱ(Position Ⅱ)

We couldn’t see the ’Wetted area’ in Section 5 too. So the cleaning effect of Section 5 can’t be expected in Section 5 without bottom of pipe too. (See TABLE Ⅸ-Ⅱ)

③ Case Ⅲ(Position Ⅲ)

We could see the ’Wetted area’ in Section 5. And we found that it was broader than Case Ⅳ. So, the cleaning effect of Section 5 can be expected. (See TABLE Ⅸ-Ⅲ)

④ Case Ⅳ(Position Ⅳ)

We could see the ’Wetted area’ in Section 5 and Section 6. So the cleaning effect of Section 5 and Section 6 can be expected. (See TABLE Ⅸ-Ⅳ)

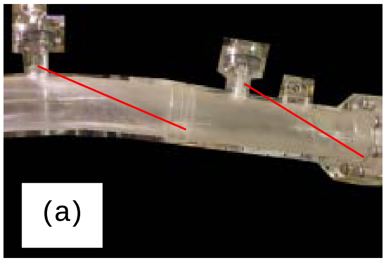
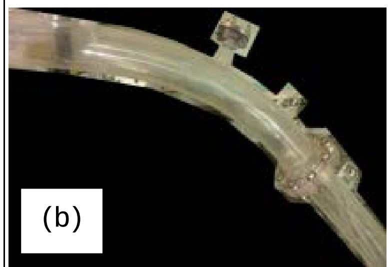
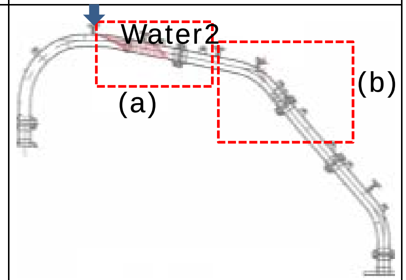
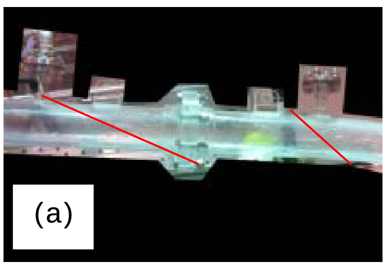
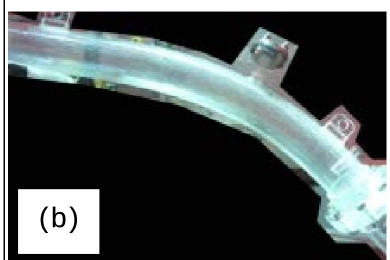
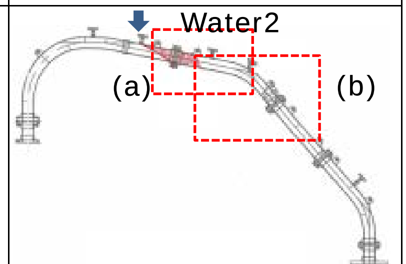
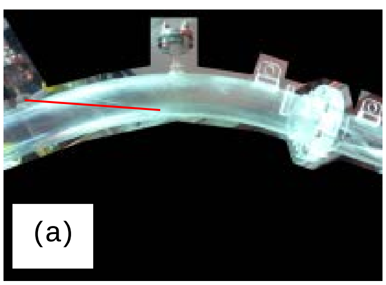
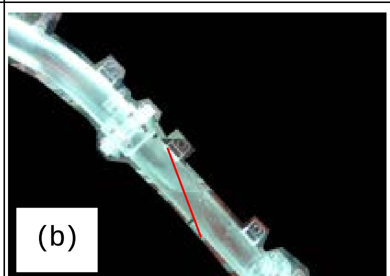
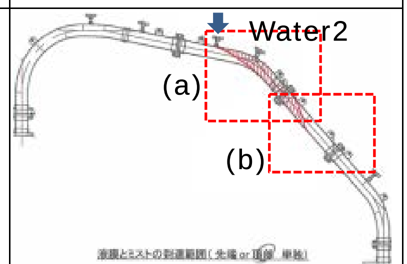
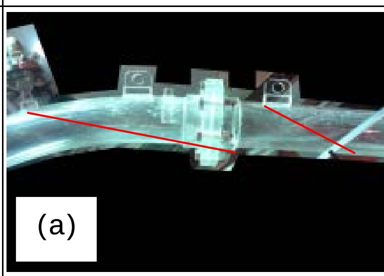
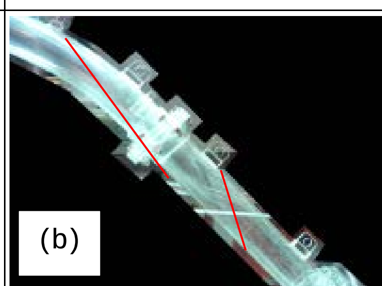
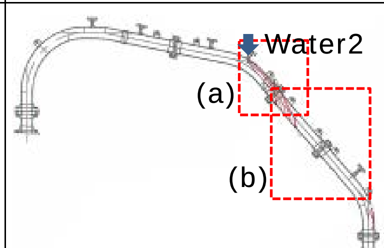
TABLE Ⅷ Test Results Changing the Position of Water2 Inlet (STEP 5)[1]

Case		Ⅰ = S	Ⅱ	Ⅲ	Ⅳ
Category	**Section 4**	○	○	—	—
	Section 5	×	×	○	△
	Section 6	×	×	△	○
Evaluation [2]		—	×	○	△

1 ○: Good, △: Average, ×: Poor, −: Unchecked
2 This is evaluated by cleaning effect of Section 5.

As above-mentioned, we observed that substantial amounts of dust deposited at Section 5 in RVL. (See Fig. 6) So, it is important that cleaning effect of Section 5 can be expected. Therefore we evaluated that Position Ⅲ is the best in Position Ⅱ-Ⅳ.

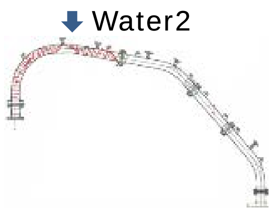
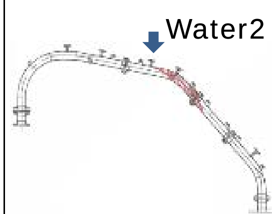
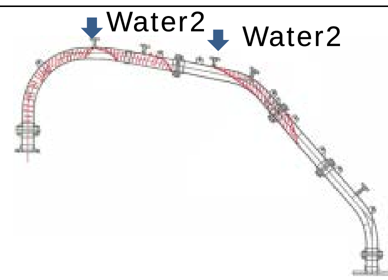
TABLE Ⅸ The Cleaning Effect in STEP 5

Case	Section 4	Section 5	Sketch
Ⅰ (S)			
	Section 4	Section 5	Sketch
Ⅱ			
	Section 5	Section 6	Sketch
Ⅲ			
	Section 5	Section 6	Sketch
Ⅳ			

Selection of the Best Cleaning Effect in STEP 1-STEP 5 (STEP 6)

As a result of STEP 4-STEP 5, we concluded that the combination of Combination ① and CaseⅢ which is the condition supplying simultaneously from two inlets concerning water2 is the best operational method with simple improvement relatively. The assumed the 'Wetted area' in this condition is shown in TABLE Ⅹ as 'Combination②'.

TABLE Ⅹ The Selection of the Best Cleaning Effect (STEP 1-5) [1]

case	Combination①	Ⅲ	Combination②[2]
Sketch			
Section 1-3	○	—	○
Section 4	○	—	○
Section 5	×	○	○
Amount of drain water	○	—	○

1 ○: Good, △: Average, ×: Poor, —: Unchecked
2 Water2 flow rate is the standard condition.

CONCLUSION AND FUTURE DEVELOPMENT

We decided the two operation methods of water cleaning system in order to improve the cleaning effect. So, we will verify that in near future as follows:

- Concerning 'Combination①', we will check the cleaning effect of exhaust pipe and the influence to LFCM operation by the actual water cleaning operation in HVF.
- Concerning 'Combination②', we will check the cleaning effect of exhaust pipe with a transparent acrylic pipe.
- Concerning 'Combination②', we will check the cleaning effect of exhaust pipe after LFCM operation in RVL.

And in future, we will consider the more improvement of the cleaning effect by the essential design change and so on based on our experience.

REFERENCE

[1] G. F. Hewitt, "Handbook of multiphase systems", ed. by Gad Hetsroni, p.2-21