A SAFETY ASSESSMENT OF HYDROGEN SUPPLY PIPING SYSTEM BY USE OF FDS

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ABSTRACT

At least once, air filling a piping from main hydrogen pipe line to an individual home end should be replaced with hydrogen gas to use the gas in the home. Special attention is required to complete the replacing operation safely, because air and supplied hydrogen may generate flammable/explosive gas mixture in the piping. The most probable method to fulfill the task is that, at first an inert gas is used to purge air from the piping, then hydrogen will be supplied into the piping. It is easily understood that the amount of the inert gas consumed by this method is much to purge whole air, especially in long piping system. Hence, to achieve more economical efficiency, an alternative method was considered. In this method, previously injected nitrogen between air and hydrogen prevents them from mixing. The key point is that how much the gas is required to prevent mixing and keep the condition in the piping safe. The authors investigated to find the minimum amount of the inert gas required to keep the replacing operation safe. The main objective of this study is to assess the effect of the nitrogen and estimate a pipe length that the safety is maintained under various conditions by using computational fluid dynamic (CFD). The effects of the amount of the injected nitrogen, the hydrogen-supply conditions and the structure of piping system are discussed.

1 INTRODUCTION

The impact of hydrogen on the environment is very small and hydrogen energy is expected to be widely adopted in our civil life. There are already over 150,000 fuel cell cogeneration systems for home use in Japan. As hydrogen using equipment like them become more widely adopted by consumers, a demand of stable and efficient hydrogen supply system increases. Moreover, Japanese government has planned to increase the number of the cogeneration system to 5.3 million by 2030[1]. To meet the increasing demand, a hydrogen piping network system is considered as one of the powerful option for stable and efficient hydrogen supply. However, the problem is that when hydrogen is supplied into constructed pipe, supplied hydrogen may mix with air in the pipe unless some protection processes. We should avoid this situation since the required ignition energy of hydrogen-air mixture is very low and it is easily ignited even by static electricity spark [2]. To overcome this problem, a method that uses a certain amount of inert gas like nitrogen has been suggested [3]. In this method, a certain amount of inert gas is supplied into pipes beforehand and it prevents hydrogen from mixing with air. In other words, hydrogen – inert gas – air sandwich structure prevents the mixing. Figure 1 shows the purging method. It shows that enough amount of the inert gas prevents hydrogen from mixing with air. Of course, the method that replaces air in entire pipe with inert gas before hydrogen supply is the simple and safest method. However, this method is not economical since it needs a large amount of inert gas especially for long piping. The question is, in the purging method, the safe pipe length obtained by using the inert gas. In other words, how much is the effect of the inert gas to prevent mixing.

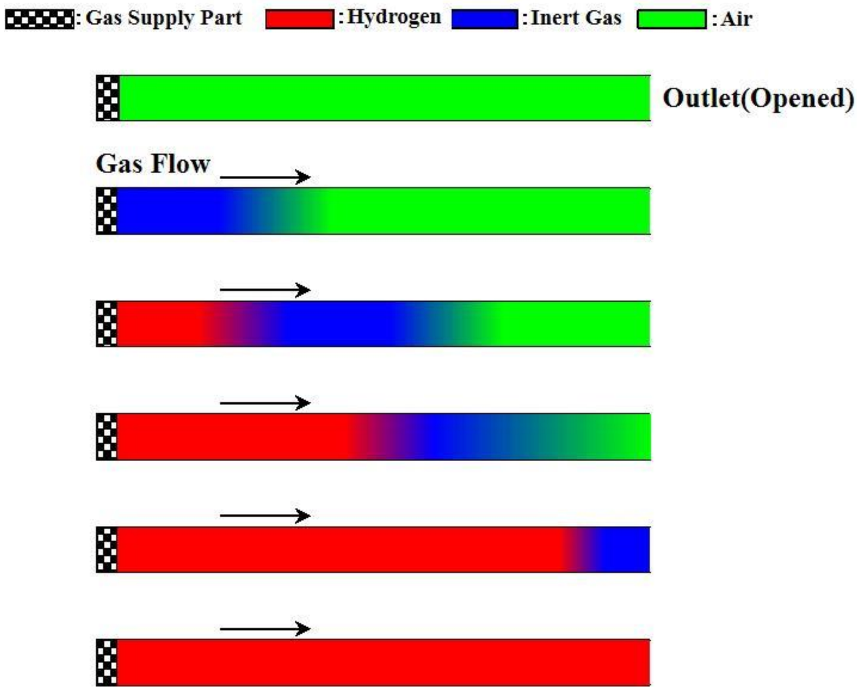

Figure 1. Chart of the purging method using the inert gas.

2 DESCRIPTION OF SAFETY ASSESSMENT

The inert gases such as argon, carbon dioxide and nitrogen are considered to be available as the gas that prevents mixing of hydrogen and air. However, in this study it is not our purpose to assess the effect of the difference of the inert gases and we considered only nitrogen as the inert gas. Let us explain about the scenario that the inert gas (nitrogen) can't prevent mixing due to its shortage. In this scenario, thickness of nitrogen layer is too thin to prevent mixing and hydrogen–nitrogen-air mixture is generated. There are two conceivable criterions to judge the risk. The first one considers the state that hydrogen just mixes with air as dangerous despite their concentrations. This criterion certainly guarantees the certainty of the safety, but it overestimates the risk. The second one judges based on the characteristics of multicomponent gas mixture, it means even if hydrogen mixes with air, this state is not necessarily judged as dangerous. For example, the mixtures that include below 4 vol. % hydrogen are not in the second criterion because the conditions of these mixtures are out of flammability. Since this second criterion leads to more certain safety assessment than the first one, the second one is used to assess the risk in this paper.

To discuss the criterion in detail, flammability range of the mixture should be considered. Based on the limits of flammability of hydrogen in hydrogen-nitrogen-air mixture [2], it is reasonable to suppose that the state of mixture which includes hydrogen of 4 vol. % and oxygen of 5 vol. % can be used as the safety standard. Figure 2 shows a transition of the gases flowing in the pipe. The layer that consists of hydrogen of 4 vol. % (Layer-H) is positioned in an upstream side of the flow. Layer-O is defined as the layer that consists of oxygen of 5 vol. % and it is positioned in the downstream of Layer-H. As hydrogen-nitrogen and nitrogen-air mixtures expand, pure nitrogen layer gradually reduces. If the amount of nitrogen gas is not enough, pure nitrogen layer disappears and Layer-H crosses Layer-O. Then a region that includes hydrogen of 4 vol. % and oxygen of 5 vol. % partly appears in pipe. At this point, the state in pipe can be judged as dangerous based on the flammability criterion. In other words, the purging operation can be safely carried out until this point. In actual operation, the safety is maintained by setting the pipe length less than the length between the gas supply part and the cross-point. The pipe length is defined as a safe pipe length (SPL) here. In this study, the safety of the purging method is assessed by estimating SPL.

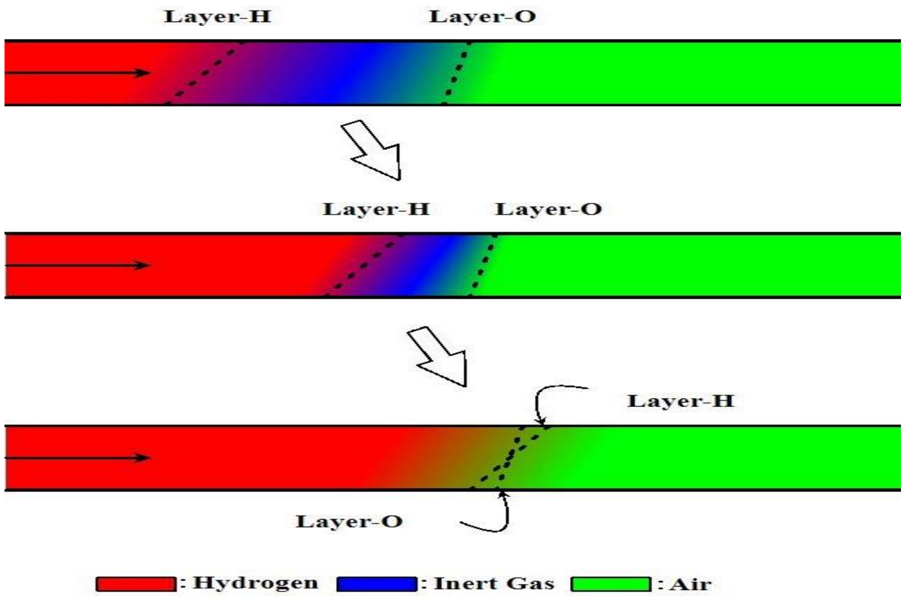

Figure 2. Transition of the gases in hydrogen-supply pipe.

3 CFD BENCHMARK EXERCISE

3.1 DESCRIPTION OF CFD CODE

FDS was used to calculate the behaviour of each gas and estimate SPLs under various conditions. FDS is free simulation software developed by NIST (National Institute of Standards and Technology) and it is mainly used to analyse the behaviour of smoke and heat transport from fires [4]. In addition to these analyses, the behaviour of hydrogen is also able to be calculated by FDS. Large Eddy Simulation (LES) was used for the analysis [5].

3.2 COMPARISON OF EXPERIMENTAL DATA AND SIMULATION RESULTS

An experiment was carried out to measure behaviour of hydrogen near a boundary of hydrogen and nitrogen by use of approximately 36mm diameter pipe [3]. A simulation model was created to assess the accuracy of the CFD code by comparing the simulation results with the experimental data. Figure 3 shows the simulation model. This is a model of a pipe system which consists of square pipe 36mm dimension, a valve and a hydrogen supply part. The length of the pipe is 10m and the calculation domain is rectangular with dimensions of 10,000 x 44 x 44 mm. The thickness of inside walls is 4mm. The valve separates two gas filling zones: hydrogen filling zone (Z_H) and nitrogen filling zone (Z_N). As initial conditions, hydrogen and nitrogen were filled in Z_H and Z_N at the atmospheric pressure, respectively. From the hydrogen supply part, hydrogen was supplied into the pipe at constant flow velocity. Therefore, as the valve opened, hydrogen in Z_H and supplied hydrogen entered Z_N. In the simulation, two flow velocity: 272mm/sec (EXP01) and 544mm/sec (EXP02) were considered. Table 1 shows comparison between the flow velocities and Reynolds numbers: Re(H_2). Re(H_2) is calculated based on the physical property of hydrogen. An outlet of the pipe was opened during the simulation and the outlet boundary was set as atmospheric pressure. The pipe which was used in the experiments described above was circular however, in FDS software, a formation of the grids is restricted to the rectangular grids, and hence the cross section was modelled as rectangular.

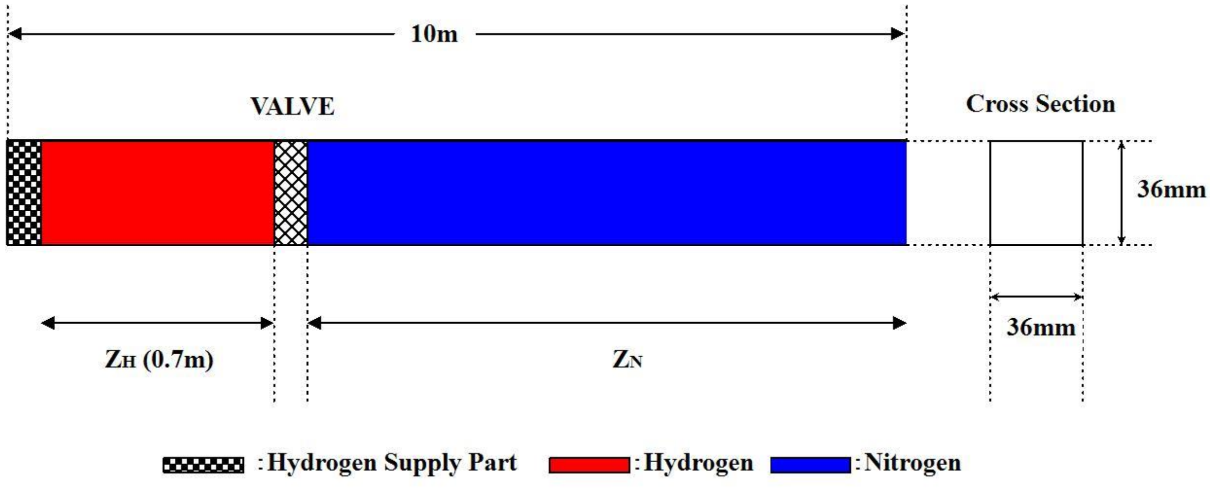

Figure 3. The simulation model for comparing with the result of the experiments.

Table 1. Comparison between the flow velocity and Re(H_2).

Flow velocity [mm/sec]	Re(H_2)
272	100
544	200

When the simulation started, the hydrogen supply part began the supply and the valve opened in 0.7seconds. In the experiments, the behaviour of Layer-H was measured in a range of approximately 1m from the valve to the outlet side. The comparison between CFD results and the experimental data is illustrated in Figure 4; the red and the blue colours refer to EXP01 and EXP02, respectively. The crosses represent the simulation results and the solid lines represent the measurements. A good agreement between EXP02 and FDS EXP02 is shown in Figure 4. These results indicate that comparatively high-velocity flow condition leads to the good agreement and even the simulation model whose cross section is square keeps sufficient accuracy.

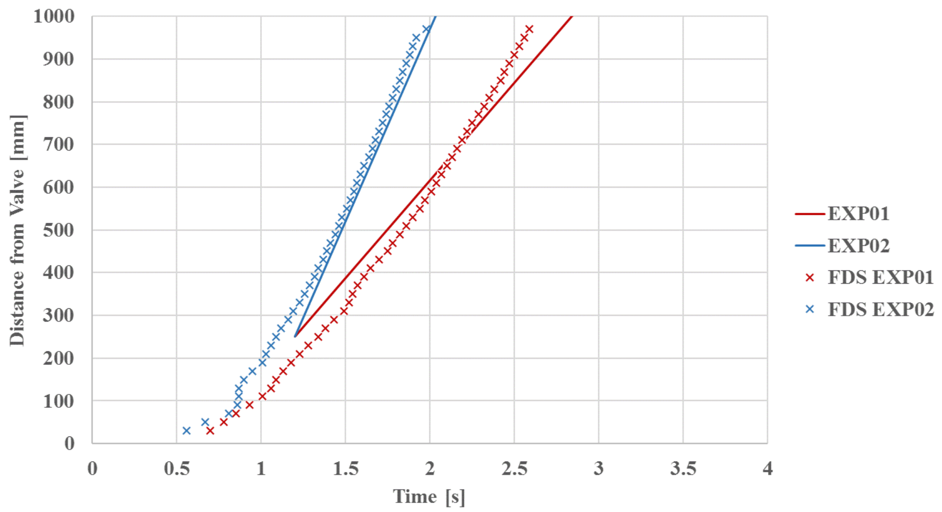

Figure 4. Comparison of simulation results and experimental data

4 MODELLING

4.1 LINEAR PIPE MODEL

The amount of inert gas, the flow velocity and the structure of pipe seemed to affect the safety of the purging operation. Therefore, the authors focused on these three factors and designed some simulation models to assess the effects of these factors. As the most basic pipe model, we created Linear-pipe model. Figure 5 shows Linear-pipe model. Almost of all parts which compose this pipe model are same as the parts of the model which is shown in Figure 3. However, Z_N was limited to a certain length and there is no valve. The outlet of the pipe was opened during the purging method and outlet boundary was set as atmospheric pressure. When we discuss the safety of the purging operation, the amount of inert gas is the most important factor because if it is not enough, hydrogen mixes with air. To assess effects caused by the difference of the initial amount of inert gas, we set the length of Z_N to 1m, 2m and 3m. Z_N1, Z_N2 and Z_N3 means that the length of Z_N equal 1m,2m and 3m, respectively. Table 2 shows the volume of nitrogen in each condition.

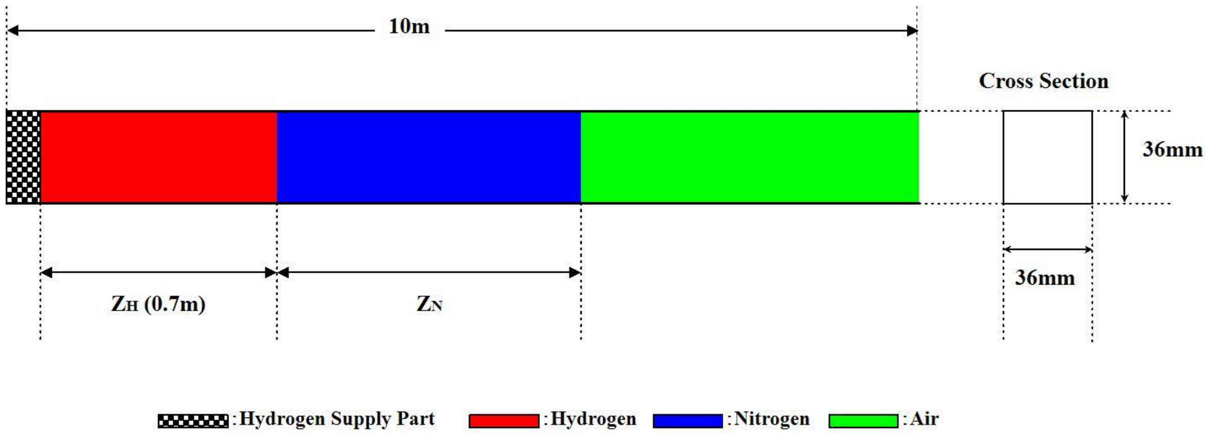

Figure 5. Liner-pipe model

Table 2. Volume of nitrogen in each simulation conditions

	Length of Z_N[m]	Volume of nitrogen [L]
Z_N1	1	1.3
Z_N2	2	2.6
Z_N3	3	3.9

Since whether the gas flow is laminar or turbulent was thought to affect the safety, an effect of the difference of the flow velocity was considered. The hydrogen-supply part supplies hydrogen at constant flow velocity and we considered five hydrogen-supply conditions. Table 3 shows comparison between the flow velocities and $Re(H_2)$ and $Re(N_2)$. $Re(N_2)$ was calculated based on the physical property of nitrogen. Combining these conditions of two factors 15 simulations were carried out by use of the Linear-pipe model.

Table 3. Flow velocity in each hydrogen-supply conditions

	Flow velocity [mm/sec]	$Re(H_2)$	$Re(N_2)$
HS1	272	100	695
HS2	544	200	1390
HS3	816	300	2085
HS4	1088	400	2780
HS5	1360	500	3475

4.2 BENDED PIPE MODEL

In addition to the two factors: the amount of inert gas and the flow velocity, the structure of the pipe has considerable factor on SPL because structures like bending parts affect the gas flow. In this study, the effects of the horizontally bending part(s) were considered and two more pipe models were created. The first one has one bended part and we defined this model as One bend pipe model. We defined the other one which has two bended parts as Two bends pipe model. One bend pipe model and Two bends pipe model are shown in Figure 6. One bend pipe model consists of two pipes. Each length of the pipes is approximately 5m and the one of pipe includes the hydrogen supply part. Z_H and Z_N are set as initial conditions and the length of Z_H is 0.7m. The length of Z_N is set to 1m, 2m and 3m in accordance with the simulation conditions. An outlet is set at one end of the other pipe. Two bends pipe model is composed of three pipes as shown in Figure 6.

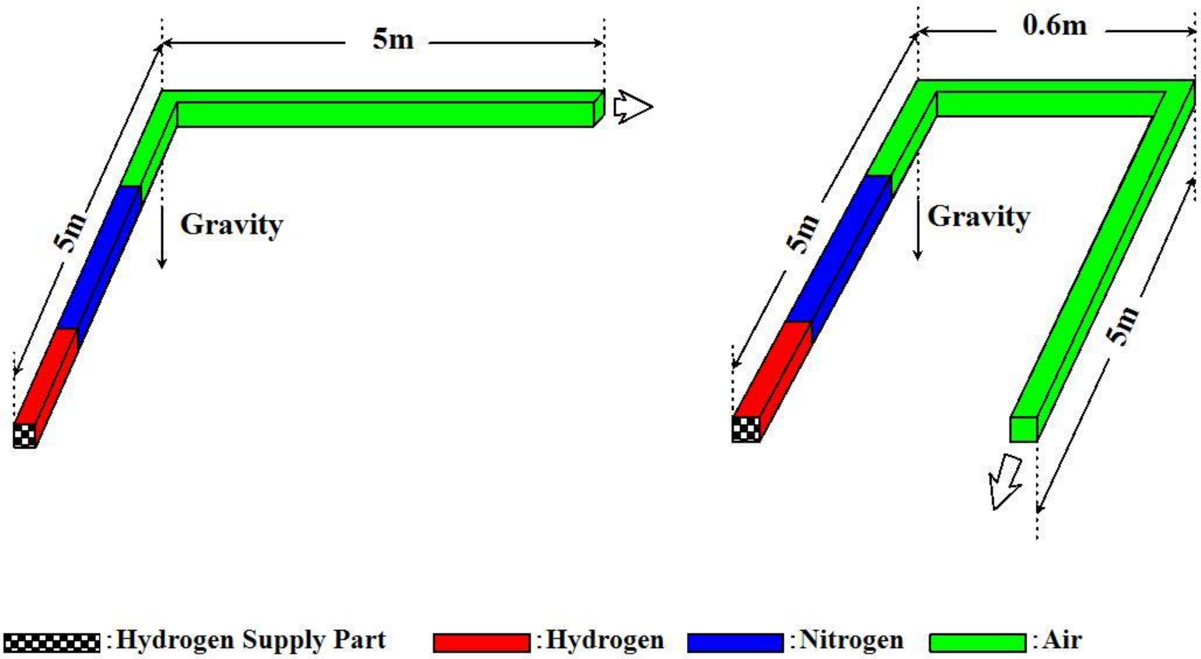

Figure 6. One bend pipe model and Two bends pipe model

5. RESULTS AND DISCUSSIONS

Forty-five SPLs were calculated under the combined conditions: the amount of inert gas (3 patterns), the flow velocity (5 patterns) and the structure of pipe models (3 patterns). Estimated SPLs are shown in Figure 7. The red, blue and green colours refer to Z_N1, Z_N2 and Z_N3, respectively. The solid lines represent the results of Linear- pipe model. The dashed lines and the long dashed double-dotted lines represent the results of One bend pipe model and Two bends pipe model, respectively. The results whose SPLs are over 10m were estimated based on the trends of Layer-H and Layer-O near the outlet of the pipe.

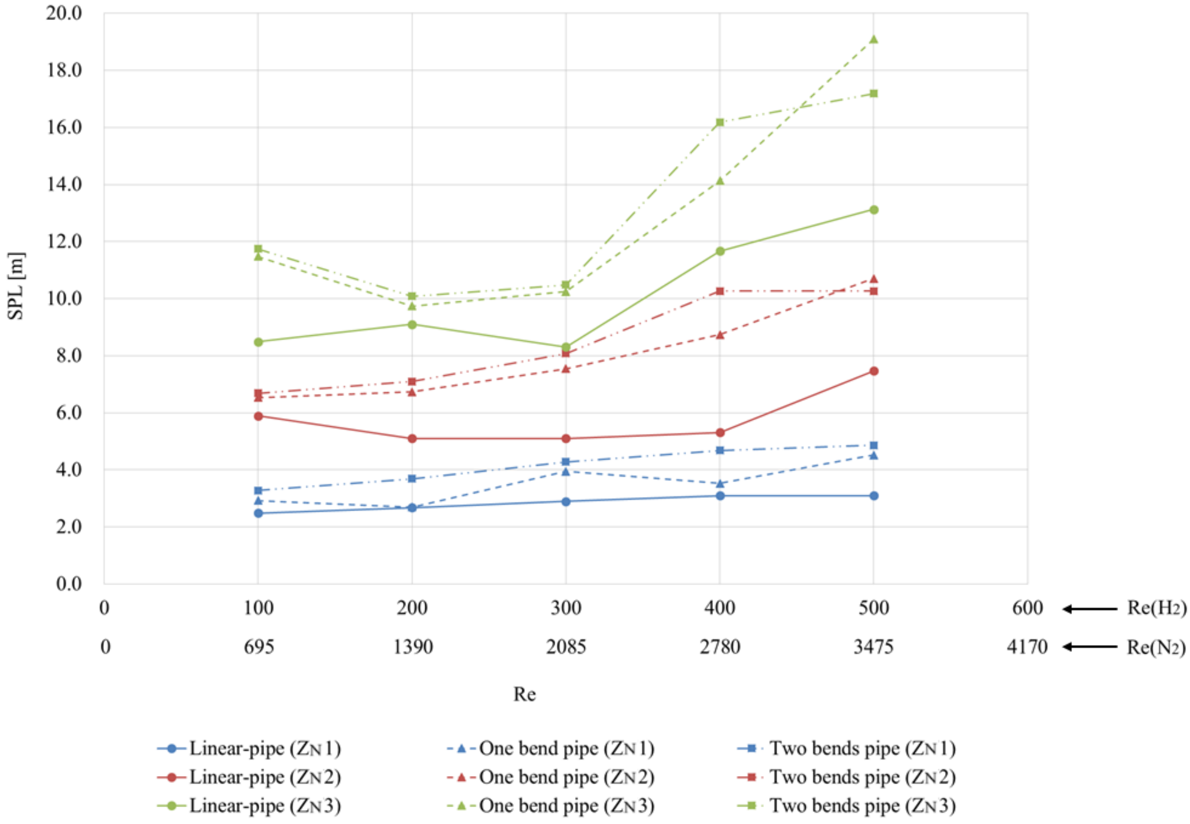

Figure 7. The results of the simulations

As shown in Figure 7, SPLs which were obtained by One bend and Two bends pipe model are almost equal or somewhat longer than those of Linear-pipe model. It seems that the horizontally bended part(s) has almost no negative influence on the safety of the purging operation. A swirl flow at the bended part(s) might not act so much to mix gases in the axial direction. The authors are planning to confirm this simulation result by experiments. Another interesting aspect of simulation results is that two bend parts do not always result in doubling the effect of each bend part. The effect of the bend parts might be affected by other piping structures such as a distance between two bend parts. This result needs more consideration including the design of the pipe model.

The blue lines indicate that SPLs are not so much affected by the flow velocity and the bend(s). On the other hand, the red and green lines indicate that both of them affect SPLs so much. Another significant point of these two colour lines is that SPLs are almost constant when $Re(N_2)$ is less than 2085 and they increase as $Re(N_2)$ increases when $Re(N_2)$ is more than 2780. The flow conditions seem different in two parts. Well known lower critical Reynolds number, about 2320, is between the two values. So, the flow is thought to be laminar for the former part and turbulent for the latter part. Figure 8 shows shapes of Layer-H and Layer-O from the side of Linear-pipe model under two different flow velocity conditions. One condition is $Re(N_2)$ equal 2085, and another is $Re(N_2)$ equal 2780. The blue and the yellow colours refer to Layer-H and Layer-O, respectively. Please note that the position of these layers are changed from the original one. The former gas flow is laminar and latter is turbulent. The important result of the simulations is that whether the gas flow is laminar flow or turbulent flow may have a great influence on SPL. However, the reason why SPL becomes longer in the gas flow of turbulent flow is not cleared in this study.

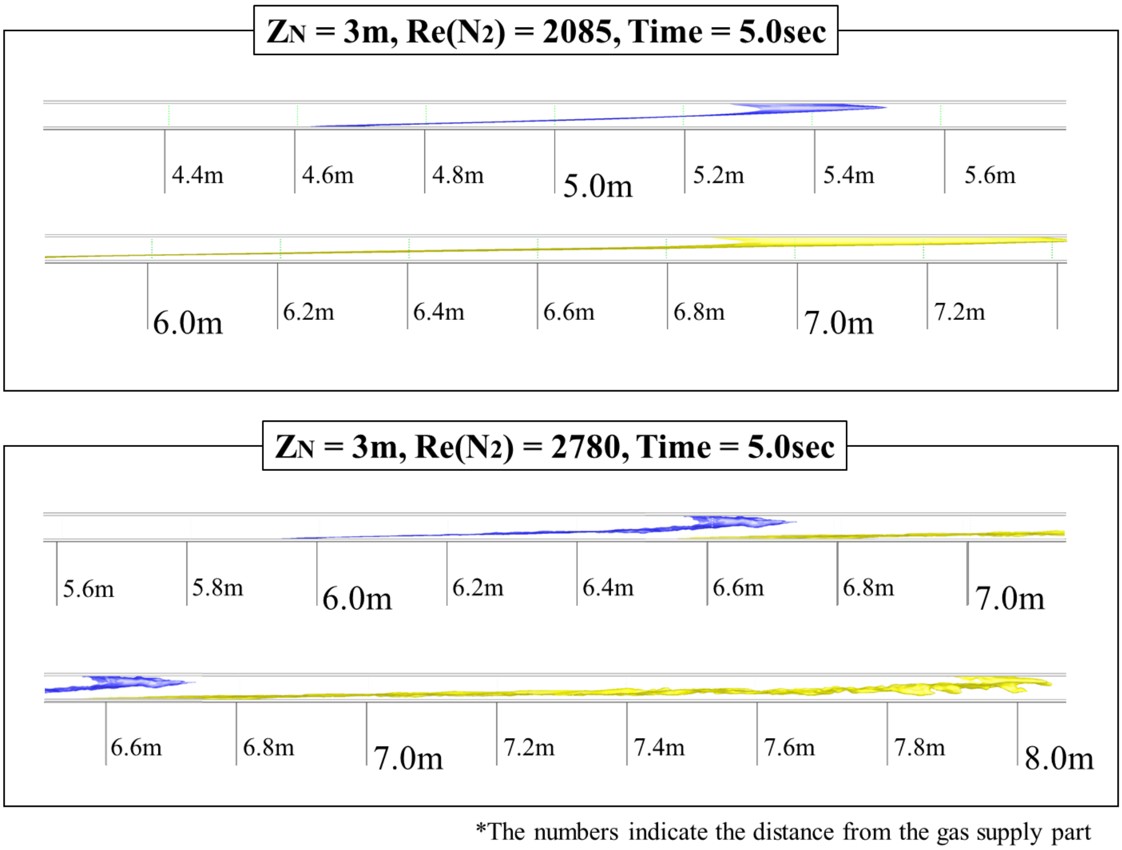

Figure 8. The shapes of Layer-H and Layer-O

6. CONCLUSIONS

This paper investigates safe pipe length of hydrogen supply required under various conditions of purging operation. Simulations were conducted to search the effect of three factors: the amount of the inert gas, the flow velocity and the horizontally bended part(s). The results from the analysis are summarized below:

(1) For Linear-pipe model, the safe pipe length is substantially constant around 2~3m under the simulation conditions that the amount of injected nitrogen between air and hydrogen is set as 1.3L. As the amount of nitrogen increases, the safe pipe length tends to be longer. Simulation results indicate that the purging operation can be safely carried out for pipes of approximately 5~7m and 8~13m, under the conditions that the volume of injected nitrogen is 2.6L and 3.9L, respectively.

(2) For One bend and Two bends pipe model, the safe pipe lengths tend to be somewhat longer than those of Linear-pipe model. These results indicate that the safe pipe length calculated in Linear-pipe model is also able to guarantee the safety even if the pipe is added the bended part(s).

(3) The safe pipe length seems to be affected by the type of gas flow: the laminar flow and the turbulent flow. The reason why the safe pipe length becomes longer in the turbulent gas flow is not cleared in this study and it needs more consideration.

7. REFERENCES

1. Agency for Natural Resources and Energy(2014), The 4th Strategic Energy Plan, <http://www.enecho.meti.go.jp/en/category/others/basic_plan/pdf/4th_strategic_energy_plan.pdf >[Accessed 14 April 2017]

2. B.Lewis, G. von Elbe, Combustion, Flames and Explosions of Gases Third Edition, 1987, Academic Press, London,

3. SHIKOKU RESEARCH INSTITUTE INC. (2016), Suiso Nettowaaku Kouchiku Doukan Hoan Gijutsu Chousa (Research of the safety techniques for piping system of hydrogen network), <http://www.meti.go.jp/meti_lib/report/2016fy/000201.pdf> [Accessed 13 April 2017]

4. FDS overview, <https://pages.nist.gov/fds-smv/>

5. FDS User Guide, <https://github.com/firemodels/fds/releases/download/FDS6.5.3/FDS_User_Guide.pdf>