

Off-take Experiment at T-junction of Vertical-up Branch on Horizontal Pipe

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Abstract

The off-take and the liquid entrainment on the air-water interface are experimentally investigated at the T-junction of vertical-up branch on the horizontal pipe. In case of the pressurizer manway opening after the loss of residual heat removal during a shutdown operation, the steam boiled from the core flows into the pressurizer via the surge line and is discharged through the manway, where the steam flow accompanies the coolant entrainment by the off-take below the inlet of surge line. This study has a focus on a shutdown operation. Test conditions are slightly over the atmospheric pressure and at room temperature. No water flow exists. An off-take is visually observed using the transparent pipes.

Scaling analysis is performed to scale down the test facility to the reference prototype, Korea standard nuclear power plant (UCN units 3 & 4). The horizontal leg and surge line geometries are scaled down as the horizontal pipe and the vertical-up branch pipe, respectively. Two different diameters of the branch pipe to have proper scaling methodologies are proposed for looking the diameter effect. The main pipe diameter (D) is 0.295m and the surge line diameters (d) are 0.05m and 0.07m. They have larger scales than those of related experimental studies. Experimental data is able to have the phenomenological similarity with the reference plant by the use of the large scale facility and by the scaling analysis.

With changes of an air flow and a water level, the onset of liquid entrainment (OLE) and the branch quality are investigated. The onset of slug transition (OST) in horizontal pipe is also observed and investigated for the relationship between the horizontal flow regime and the off-take phenomena. The scale effect of branch pipe exists in the OLE and the OST data. The branch quality is strongly affected by the flow regime in horizontal pipe. The stratified flow is more persistent up to larger air flow than the existing model. These experimental results will be bases of studies in phenomenological modeling and the proper scaling methodologies in the future works.

1. Introduction

In case of the pressurizer manway opening after the loss of residual heat removal during a shutdown operation the coolant is entrained by the off-take phenomenon at the inlet of the surge line and is discharged through the manway opening. It revealed an off-take has the significant effects on the maintenance of coolant inventory. An off-take is the phenomenon that the entrainment and pull-through of liquid droplets of them occur on the horizontal liquid interface by the gas flow into the vertical-up branch pipe. Steam boiling in core changes the collapsed level into the mixture level, which raises the coolant level. When the coolant level is initially close to the mid-level of the hot-leg after the loss of residual heat removal, the off-take having a shape of mount occurs and the discharge quality through the surge line is close to 1. As the water level rises closer to the surge line inlet by a formation of mixture level, the off-take phenomenon becomes the coolant interface split at the T-junction of the surge line and the hot-leg and the discharge quality dramatically drops. Such a liquid pull-through by an off-take shifts the coolant inventory from the core to the pressurizer, and, in turn, threatens the core stability.

In the past studies, the branch flow at T-junction was experimentally performed to investigate the small-break loss-of-coolant-accident (SB-LOCA) and its modeling was implemented into the thermal-hydraulic codes, e.g., RELAP5. Small breaks are simulated as the branch pipes. They examined the liquid entrainment or the liquid pull-through at various branch orientations and obtained empirical correlations and entrainment models. A review of the previous works indicates the following common deficiencies, especially in applying to the shutdown operation:

- ◆ Most of the experimental data were obtained in test facilities whose geometric conditions and scale were too far from the prototypic geometries. For instance, the hot-leg diameter in prototype is 1.067m (Korea standard NPP), whereas those of previous test facilities were within 0.2m. A branch pipe simulated as the small size of breaks, therefore the diameter ratios of the branch-to-main pipe (d/D) were smaller than that of the surge line-to- hot-leg.
- ◆ Experimental conditions were high pressures and high flows because of the SB-LOCA simulation. Therefore, the depressurization is very large around a break, which may cause the liquid flashing or the critical discharge flow. In low pressures and low powers of shutdown condition, the force balance between the upward flow of gas and the gravitation is a mechanism to govern an off-take phenomenon. It is preferable that these two hydrodynamic parameters are examined without pre-pressurization condition
- ◆ Scaling analysis is needed for test facilities, which have the basis for phenomenological similarities to the prototype. The RELAP5 code has a horizontal stratification entrainment model whose correlations results from the previous branch flow studies (Smoglie, 1984; Schrock et. al., 1986). This model does not represent the geometric scale effects, especially for the branch diameter.

From these literature surveys, the objective and scope of the present study are determined. This study is in progress, and the primary objective of this study is to obtain the experimental data for an off-take phenomenon using the test facility based on the scaling analysis in the shutdown operation conditions. Several features of this research are listed as follows:

- ♦ To indicate the shutdown operation conditions, the off-take experiments are performed at nearly atmospheric pressures and at sub-critical flows. The test scope of the branch orientations is narrowed down only for the vertical-up branch to simulate the surge line on the top of the hot-leg.
- ♦ Experimental data are obtained as follows; onset of liquid entrainment, onset of slug transition in hot-leg and branch quality.
- ♦ Test facility is designed according to the scale methodologies resulting from the scaling analysis, which enables the scale similarity with real plant. The scale of test facility is large compared to the previous one to minimize the phenomenological distortion due to scaling down.

2. Scaling Analysis for Test Facility

Prior to the detailed design of test facility, scaling analysis is performed and results in the proper scaling methodologies to apply to the test facility. The Korea standard NPP (UCN Units 3&4) is selected as a prototype plant. Firstly, the scale ratios of a gas flow rate (Q_g) and an area (a) of horizontal pipe are determined as 1/25 scale, where the gas velocity (v) ratio in the horizontal pipe is preserved. This scaled-down ratio is lower than that of the existing integral test facilities and the previous separated test facilities.

$$[Q_g]_R = [va]_R = a_R$$

According to the above value of scale ratio other scale ratios are determined. The CCFL similitude is applied to the scaling of the horizontal pipe diameter (D) as follows:

$$[j_g^*]_R = 1 \rightarrow [D]_R = [Q_g^{2/5}]_R \quad (2)$$

From the above result, D is scaled down from 1.067m to 0.295m. This scale is closer to the real plant geometry than that of the previous experiments. The existing correlation for the branch quality is generally a function of h/h_b , where h_b has the relation of $[h_b]_R = [Q_g^{2/5}]_R$ from the correlation for the onset of liquid entrainment (OLE). If the relative water level ($h^* = h/D$) keeps the ratio of $[h^*]_R = 1$, the above Equation (2) satisfies the branch quality similarity as follows:

$$\begin{aligned} [x]_R = 1 \rightarrow [h/h_b]_R = 1 &\rightarrow \left[\frac{h}{Q_g^{2/5}} \right]_R = \left[\frac{Dh^*}{Q_g^{2/5}} \right]_R = 1 \\ &\rightarrow [D]_R = [Q_g^{2/5}]_R \text{ (if } [h^*]_R = [h/D]_R = 1) \end{aligned} \quad (1)$$

The length (L) of the horizontal pipe is scaled as the same as the D -scale ratio ($[D]_R$) of 0.276, which is on the basis of experimental results (Kang, 1999) for CCFL in the hot-leg.

$$[L/D]_R = 1 \rightarrow [L]_R = [Q_g^{2/5}]_R \quad (4)$$

The branch pipe is scaled down as two different diameters using the velocity similitude ($[V]_R = 1$) and the CCFL similitude ($[j_g^*]_R = 1$), respectively.

$$[d_1]_R = [Q_g^{1/2}]_R = 0.2$$

$$[d_2]_R = [Q_g^{2/5}]_R = 0.276$$

3. Test Facility of Off-take Experiment

Test facility has been designed and constructed based on the scaling analysis. Figure 1 is the overall schematic diagram of the test facility, which consists of an air-water supply tank, a horizontal pipe, branch pipes having two different diameters, an air-water separator and an entrained water collecting tank. Additionally, an air blower system, its control panel set and various measuring instruments are installed to the test facility. The hot-leg and the surge line in real plant are scaled down as the horizontal main pipe and the branch pipe, respectively. All these pipes are transparent for a visual observation. Test pipes have relatively large diameters compared to the previous experimental facility. Therefore, the test facility needs a large amount of gas flow, which is the reason that an air is used for working gas instead of as steam. The reinforcement structure for an air-water supply tank, a horizontal pipe and a T-junction are supplemented to endure the slugging oscillation impact while performing experiments. In Figure 1, the two-phase branch flow is separated into the entrained water and the gas flow in the air-water separator. Thereafter, the entrained water is collected in the collecting tank, where the amount of collected water is used for calculating the branch quality. The diameter and length of the horizontal pipe are 0.295 m and 0.935 m, respectively. The branch diameters are 0.05m and 0.07m. Table 1 shows the scale comparison of the real plant and the test facility. The experiment is performed at room temperature. The system pressure ranges from 1 bar to 1.3 bar. Slight pressurization is purely due to the air blowing. The maximum air flow rate in experiments is up to 18,000 lpm. An air ring blower has a capacity of 25,000 lpm at atmospheric pressure.

4. Experimental Results

Using the air-water test facility, the off-take tests are performed. Experimental works are divided into three parts as follows:

- ◆ Onset of liquid entrainment
- ◆ Branch quality
- ◆ Onset of slug transition in horizontal pipe.

Discrimination of the onset of liquid entrainment (OLE) depends on the visual observation, which means the OLE data may include a bit ambiguity resulting from visual discrimination. However, the parameter of h_b

including OLE information is used for the existing correlations for the liquid entrainment. As the previous works do not represent the OLE criteria in detail, the OLE criterion for this test is firstly defined; By an entrained droplet observation, the droplet is entrained and deposited on the inner wall of branch pipe and horizontal pipe, thereafter, the deposited droplet water moves toward a pipe exit on the wall.

Branch quality is strongly affected by the horizontal flow regime. As an increase of the gas flow the flow regime transits from stratified flow to slug flow. The onset of slug transition (OST) results in the dramatic decrease of the branch quality. In a stratified flow in horizontal pipe, the water interface has a mounted shape, where an off-take is the liquid entrainment. In a slug flow, the water interface becomes extremely unstable and splits into the branch pipe at T-junction, where an off-take is the pull-through that a liquid is entrained as a bulk.

The branch diameter (d) effects are investigated using two different diameters of the branch pipe. As a result, the OLE and the OST have d -scale effects.

As the diameter (D) of the horizontal main pipe is the largest scale in existing test facilities for off-take phenomena till now, the slugging impact is large enough to break the test pipe in the low quality experiments with slug flow regime. Hence, the experimental range of a relative water level (h/D) is limited within a value of 0.4 in spite of the reinforcement of structures while testing.

4.1. Onset of Liquid Entrainment (OLE)

The gas flow rate required for the OLE increases with an increase of h/D . In Figure 3, 70 mm branch pipe needs more air flow rate than 50 mm branch pipe. This represents the d -scale effect exists in OLE data, which results from the fact that air requires a larger flow rate to reach the gas velocity enough to overcome a gravitation as the diameter of branch pipe increases. The dashed line is the correlation of the KfK in Germany (Smoglie, 1984), which is used for the RELAP5 code. This existing correlation well predicts data in a range of an overall OLE, but does not properly represent the fact that the d -scale effect exists.

The OLE results have an important effect on the quality correlation because OLE is represented as a function of h/h_p . Thus, the revised correlation that is able to represent the d -scale effect is more preferable for better prediction than the existing correlation. Figure 4 is the comparison of the present and previous data with the prediction by the correlation. From the experimental experiences and the data comparisons, the OLE data may have a deficiency that their distribution is dispersed due to the ambiguity of an OLE criterion, which may leads a bad reproducibility. When we say that the importance of the OLE data and correlations is to normalize the flow or water level conditions and to represent the branch quality as such a normalized parameter, it is preferable to find an alternative parameter from a discernible phenomenon, e.g., the onset of slug transition (OST).

4.2. Onset of Slug Transition (OST)

Stratified to slug transition in the horizontal pipe is experimentally investigated because of its important effect on a branch quality. From the OST observations, the first slugging always occurs at the T-junction,

thereafter the slug flow spreads over the entire horizontal water interface.

Figure 5 shows a plot of normalized water level by an OLE (h/h_b) versus relative water level (h/D). In this Figure, the value of h/h_b is not only affected by the branch diameter, but also by the h/D .

Figure 6 is the comparison of the OST among the present data, the previous data, and the predictions by the model, where the solid curve called as T-D correlation (Taitel, Dukler, 1976) is used in the RELAP5 code to predict the stratified to slug transition in horizontal pipe. Definitely, the OST in the present data occurs at higher velocity in horizontal pipe than those in the previous data and model. Therefore, the branch quality can be remained as high value close to unit. These results mean the stratified flow in the horizontal leg is persistent up to higher gas velocities than those expected by the previous results. Such a tendency may result from relatively low L/D and large D in the horizontal geometry compared to the previous OST experiments. In these two figures, the d-scale effect also exists in the OST data.

4.3. Branch Quality

The branch quality data are obtained with changes of the air flow rate and the relative water level (h/D). To obtain steady-state data, the entrained water in the collecting tank is measured while the water level is maintained as a constant value. The quality is strongly affected by the flow regime in horizontal pipe. Quality data is divided by the low values and the high values according to the flow regime conditions in horizontal pipe. In high quality experiments, total 48 data are obtained whose values are nearly the same as unit (>0.96) in ranges of h/D from 0.15 to 0.45. Figure 7 shows the high quality data. In low quality experiment, only 10 data are obtained up to now. Lack of data in low quality region results from the slugging oscillation and more data acquisition is in progress to obtain data over the entire quality region.

Figure 8 is the comparison of the quality data and the existing correlation. The solid curve is the UCB correlation, which is used in the RELAP5 code. This correlation is developed using their low quality data together with KfK's high quality data. Such a unified correlation to cover the entire quality region has a shape of the smooth curve, which results in the differences between the data and the correlation near the transition region. The dashed curve is the KfK correlation only for representing the high quality. This correlation well predicts only the high quality data. Figure 8 is a plot of quality (x) versus h/h_b . In the domain using the h/h_b as x-axis, the x-axis values of h/h_b that the OST occurs have some range with changes of h/D or d . Therefore, the quality correlation should be plotted as a variable curve for better prediction of the OST occurrence in various flow and level conditions.

Figure 9 is the comparison of the same quality data in a plot of x and h/h_s , where h_s means the water level from the top of horizontal pipe at the OST. Therefore, in the left side of the vertical dashed line of Figure 9, the horizontal flow regime is the slug flow. On the contrary, the right side represents the horizontal stratified flow. In this $x-h/h_s$ domain, the OST occurs on a dashed line, not in some range. Conclusively, a plot of $x-h/h_s$ instead of $x-h/h_b$ represents the quality correlation can be expressed as a single curve because the OST occurrence at various experimental conditions only corresponds to $h/h_s=1$. The solid curve is the existing quality correlation of CENG (Micaelli et al., 1988), which well predicts the present data. This curve is separately

correlated for the stratified flow and the slug flow that correspond to a high quality and a low quality, respectively.

5. Conclusions

In this paper, the off-take phenomenon and the branch scale effects at T-junction with a vertical-up branch in horizontal pipe are experimentally investigated. Also, the data of an onset of liquid entrainment, an onset of slug transition and a branch quality are obtained. Experimental results are analyzed and compared to the previous studies and to the existing models. As a result, the following conclusions can be summarized:

- ♦ The scale effect of the branch diameter exists in the onset of liquid entrainment and in the onset of slug transition. As a branch diameter increases, larger gas flow is required for the liquid entrainment and the liquid pull-through.
- ♦ In the present experiment, the stratified flow is persistent up to higher gas velocity, which may result from relatively low L/D ratio and large D scale in the horizontal geometry.
- ♦ Branch quality is strongly affected by the flow regime in the horizontal pipe. The quality can be separately considered as low and high quality regions because it dramatically decreases from its value close to unit when stratified to slug transition occurs. Likewise the CENG correlation forms, two separate correlations of the branch quality are more preferable than the existing unified correlation used in RELAP5.

Nomenclature

- a Area of hot-leg (horizontal pipe)
 d Diameter of surge line (branch pipe)
 D Diameter of hot-leg (horizontal pipe)
 h Water level from the top of horizontal pipe
 h_b Onset of liquid entrainment (OLE)
 h_s Onset of slug transition (OST)
 L Length of horizontal main pipe
 j_g Superficial velocity of gas
 Q_g Volumetric air flow rate of gas
 $[]_R$ Model to prototype ratio ($[x]_R = x_{\text{model}} / x_{\text{prototype}}$)

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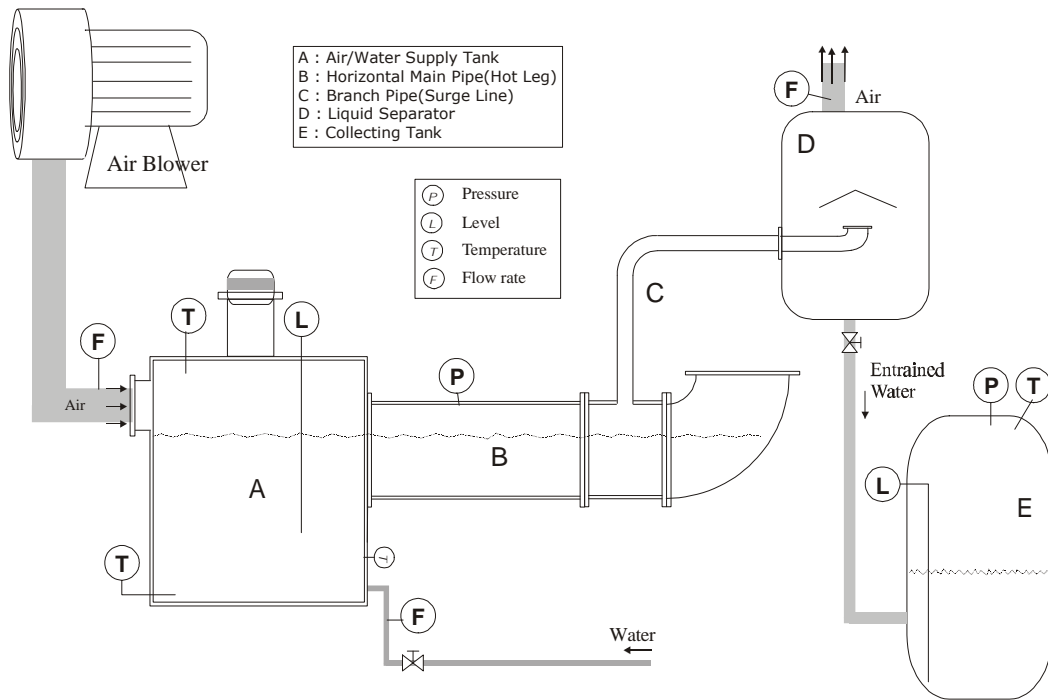


Figure 1. Overall schematic diagram of test facility

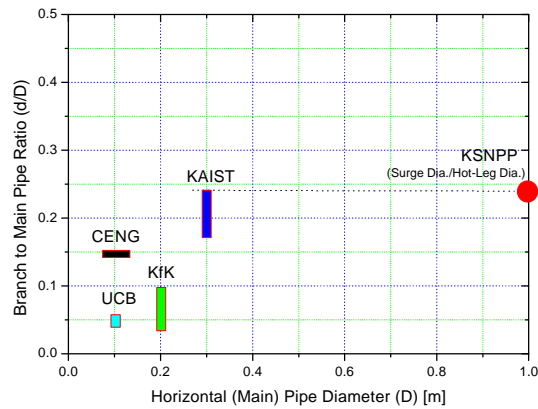


Figure 2. Scale comparison of test facilities with Korea standard NPP

Table 1. Scale comparison between prototype and test facility

Scaling Parameter		UCN-34	KAIST
Hot Leg Diameter	[m]	1.067	0.295
Hot Leg Length	[m]	3.338	0.935
Surge Line Dia.-1	[cm]	25.7	5.00
Surge Line Dia.-2	[cm]		7.00
Gas Flow Rate	[Kg/s]	4.3	0.172
d/D Ratio		0.241	0.174-0.241

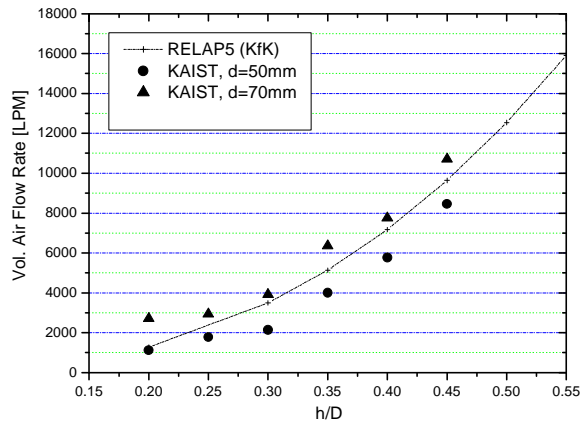


Figure 3. Air flow rate on OLE

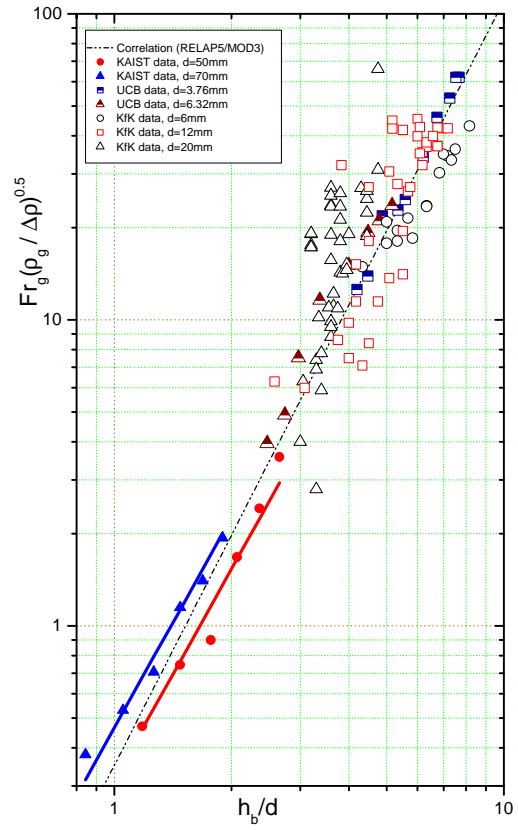


Figure 4. Comparison of OLE data

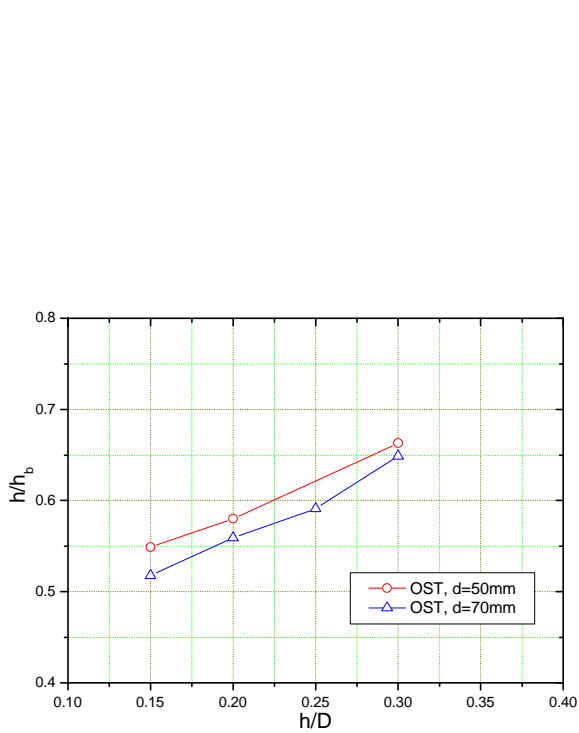


Figure 5. Normalized water level on OST

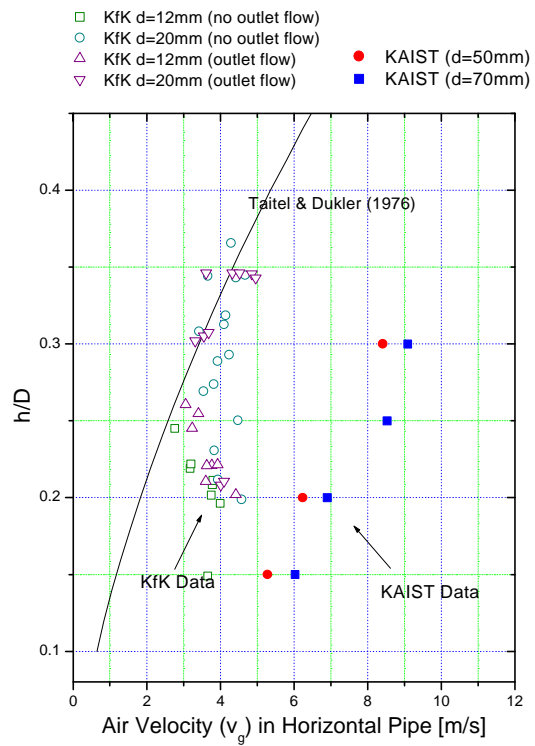


Figure 6. Comparison of OST data

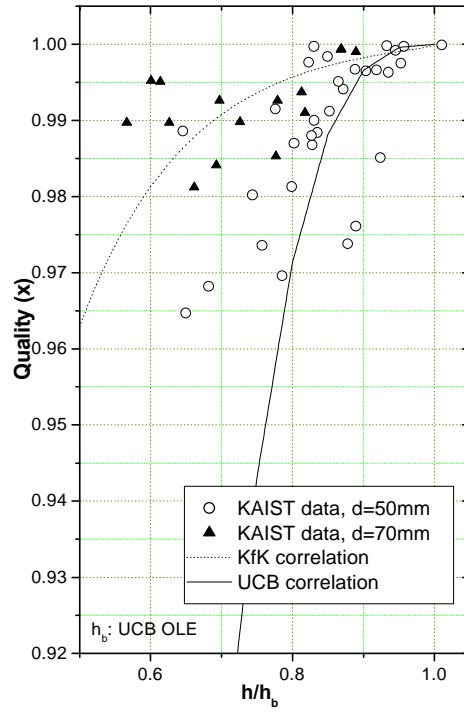


Figure 7. High quality data

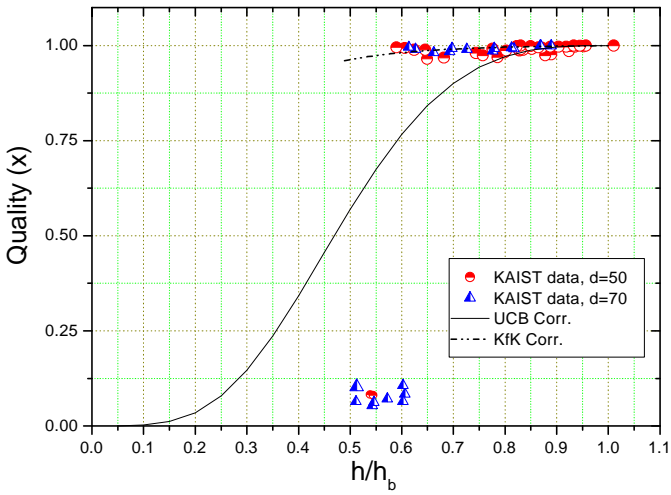


Figure 8. Quality data and existing correlations h/h_b

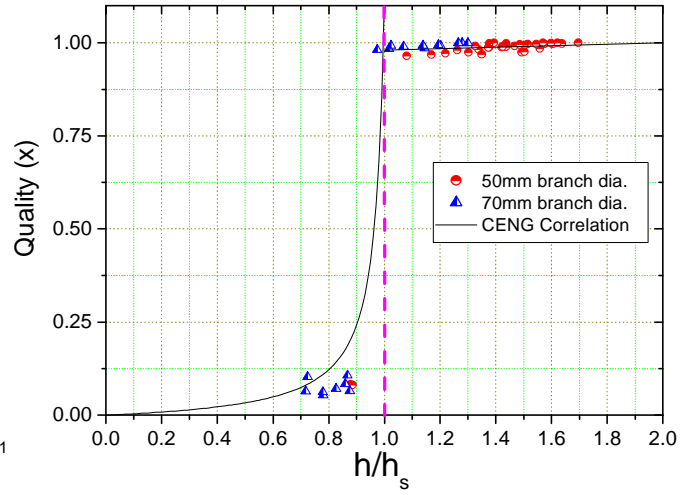


Figure 9. Quality data and existing correlations h/h_s