ON THE EFFECT OF WATER FILM ON FLOW-INDUCED PULSATIONS IN CLOSED SIDE BRANCHES IN TANDEM CONFIGURATION

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ABSTRACT
Previous studies demonstrate that the presence of liquid strongly influences the pressure pulsation amplitudes of flow induced pulsations. In particular, in case of annular flow (thin liquid film on the walls) the pulsations can be eliminated. The present study aims at evaluating the contribution of the liquid film to the pulsation reduction.

Experiments have been performed in a tandem configuration with two side branches upward oriented. The side branches have the same diameter as the main pipe.

A first set of experiments has been conducted with the injection point located far upstream the upstream side branch. To isolate the sole effect of the film, a second and a third set of experiments have been performed with the injection point located close upstream the T-junction with the injection such that a thin film only was generated.

In the first configuration (far upstream), the pulsation level decreases with increasing liquid rate. The reduction in amplitude compares well with the assumption of added damping in the length between the two side branches.

A similar decrease in pulsation amplitude was obtained in the second configuration. However, the amplitude reduction depends on the local liquid flow pattern at the (upstream) side branch and in particular on whether liquid bypasses the side branch or it interferes with the shear layer.

This indicates that acoustical damping is the main effect and small amounts of liquid do not significantly interfere with the shear layer.

INTRODUCTION
Piping layouts typically used in gas transport systems are characterized by branches along the main process flow line. The presence of T-junctions can have a dramatic effect on the safety and on the productivity of the plant. In fact, these configurations are characterized by trapped, or nearly trapped acoustic modes, which favor the occurrence of high-amplitude Flow-Induced Pulsations, i.e. whistling. Pressure pulsations are driven by vortex shedding at the upstream edge of each side branch (Figure 1a). Under particular circumstances, this fluid dynamic phenomenon turns into an acoustical one, leading to dangerous conditions of fatigue caused by large structural vibrations.

Over the past 70 years, the effects have been experienced in several fields. For a detailed overview of the historical development and experiences see Tonon et al. (2011), Graf and Ziada (2010), and Ziada and Lafon (2014).

However, almost all these studies are for single phase gas and limited research has been done to determine the effect of the presence of liquids. Recently, more attention has been paid by the scientific community, either in corrugated pipes (Belfroid et al., 2013; Golliard et al., 2013; Belfroid et al., 2014) or in pipes with side branches (Sanna and Golliard, 2014a-b; Shoeibi Omrani et al., 2012). For instance, the experimental investigations of Golliard et al. (2013) were conducted to investigate the effect of small quantities of liquid on damping both in a smooth pipe and in a corrugated pipe (internal diameter 49.0x10^-3 m), at different gas velocities. In addition, Uchiyama and Morita (2013) proposed a method for predicting the resonance frequency in a piping system with nearly saturated steam conditions.

Concerning pipes with T-junctions, tests were recently performed with a mixture of gas and water on two configurations of two closed side branches along a main pipe, both in tandem (Sanna and Golliard, 2014b) and in quasi-cross configuration (Sanna and Golliard, 2014a). In his tests, into a 2-inch inner diameter pipe Sanna injected liquid at different flow rates together with air. Pressure pulsations generated by the
grazing air flow were measured at the closed end of the two side branches. It was observed that at the highest liquid injection rates, when the distribution of water and air mixture was clearly annular, the pressure amplitude decreased. The liquid film, typical of annular flow patterns, was considered one of the main causes of the reduction of the pulsations amplitudes. The liquid film affects the shear layer instability via both the presence of liquid droplets in the shear layer and via changes in the boundary layer profile at the cavity edge (see Figure 1a).

The aim of this work is to investigate the sole effect of the liquid film on the FIPs trend. To investigate it in the tandem configuration, three different sets of experiments are performed.

This configuration has been chosen because of the extensive experimental available data. Indeed, when tuned to maximum pulsation levels the configuration is characterized by a standing pressure wave whose wavelength perfectly fits in the resonator. The standing pressure wave has the nodes at the T-junctions and the maximum amplitudes at the closed end of each side branch (Figure 1b).

Different volumetric flow rates $Q_L$ are injected in a horizontal smooth main pipe where air flows at different air volumetric flow rates $Q_G$.

In this paper, the experimental method and the design of the experimental setup are first presented. Last, the results are shown and discussed.

**NOMENCLATURE**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>A</td>
<td>Upstream length [m]</td>
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<tr>
<td>B</td>
<td>Middle length [m]</td>
</tr>
<tr>
<td>C</td>
<td>Downstream length [m]</td>
</tr>
<tr>
<td>D</td>
<td>Injector location [m]</td>
</tr>
<tr>
<td>D1</td>
<td>Length of the upstream side branch [m]</td>
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<tr>
<td>D2</td>
<td>Length of the downstream side branch [m]</td>
</tr>
<tr>
<td>$D_{mp}$</td>
<td>Diameter of the main pipe [m]</td>
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<tr>
<td>$D_{sb}$</td>
<td>Diameter of each side branch [m]</td>
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<tr>
<td>$\delta$</td>
<td>Ratio of the main pipe inner diameter to the side branch inner diameter [-]</td>
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<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
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<td>FIP</td>
<td>Flow Induced Pulsation</td>
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<tr>
<td>$f_n$</td>
<td>Resonant frequency [Hz]</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>No slip Liquid Volume Fraction [-]</td>
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<td>$Q_G$</td>
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<td>$Q_L$</td>
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<td>$\rho$</td>
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<tr>
<td>Sr</td>
<td>Strouhal number [-]</td>
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<td>$U_{SG}$</td>
<td>Superficial Gas Velocity [m/s]</td>
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<tr>
<td>$U_{SL}$</td>
<td>Superficial Liquid Velocity [m/s]</td>
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Figure 1. Double side branch - Tandem configuration: Generation of the vortex shedding and mechanism loop (a), and standing pressure wave (b).
DESIGN OF THE EXPERIMENTAL SETUP AND EXPERIMENTAL METHOD

In this section, the technical details of the facility are firstly provided, followed by the description of the methodology used to conduct the experiments.

Setup

The resonator chosen is characterized by the distance $B$ between the side branches equal to the double of the length of the side branches ($D1=D2=B/2$). Figure 2 provides a general description of the setup tested. Note that the side branches are mounted upwards to avoid accumulation of water due to gravity.

The inner diameters of the main pipe $D_{mp}$ and $D_{sh}$ of the side branches are 1 inch.

The edges of the T-junctions are sharp and the material of the whole facility is transparent Plexiglas with a wall thickness of $3.5 \times 10^{-3}$ m.

The lengths are the following (see Figure 2 and Table 1):
- $A$, upstream length. It is defined as the length between the axis of the upstream side branch and the inlet of the system. It is equal to 1.70 m, which corresponds to about 68 $D_{mp}$;
- $B$, middle length. It is defined as the distance between the axes of the two side branches and it is equal to $B=53.6 \times 10^{-2}$ m;
- $C$, downstream length. It is the distance between the axis of the downstream side branch and the separator. It is equal to $C=1.34$ m;
- $D$, injector location. It is defined as the distance between the axis of the upstream side branch and the water injection point;
- $D1$ and $D2$, physical length of the side branches, i.e. the length between the closed end and the main pipe inner surface.

Concerning the lengths $D1$ and $D2$, they were chosen such that their acoustic length is 0.268 m. The frequency corresponding to the first acoustic mode $f_1$ is about 320 Hz. The definition of the acoustical length of the side branches includes the length corrections. According to the model proposed by Nederveen et al. (1998), the no-mean-flow acoustic correction length for this resonator ($\delta = 1$) is equal to $4.0 \times 10^{-3}$ m. $D1$ and $D2$ (physical lengths) are thus equal to 0.264 m.

The upstream and downstream lengths $A$ and $C$ were chosen based on two considerations: minimal influence of other acoustical resonances on the Tandem resonance in the velocity bandwidth of interest and sufficient multiphase flow development length. Thus, a 1D-acoustical-No flow model was built to study the influence of other resonances on the main ones. It is similar to the model of Tonon (2011) and it is based on lumped elements (Pierce, 1981; Dowling and Ffowcs Williams, 1983; Munjal, 1987; Boden and Åbom, 1995; Polifke, 2007). The system (Figure 2) has been divided into basic elements: straight pipe, T-junction, area expansion, closed end. In straight pipes, variables are related by the plane wave conditions. At the T-junctions, as well as for area expansions, continuity of the acoustic volume flow and the continuity of the acoustic pressure are imposed. At each T-junction, a source is also added to represent the sound source term. For the 1D simulations, a reflection coefficient equal to 0.86 and an open boundary condition have been imposed, upstream and downstream respectively. The first is the acoustical reflection coefficient at a frequency equal to 320 Hz of the system inlet, i.e. the 2-pipe main injector used to drive air and water into the main pipe.

The entrance length is 68 $D_{mp}$ which is sufficient development length in case of stratified flow. In case of annular/dispersed flow this is on the edge. However, the expected onset of entrainment is at $U_{SG} = 19$ m/s (Ishii, 2003). This is at or above the measurement range for the current experiments. Therefore, no or very low entrained fractions are expected and developed flow is assumed.

The final lengths of the entire system are reported in Table 1.

![Geometrical details of the configuration tested.](image)

Table 1. Physical and equivalent acoustical lengths of the experiments setup (Figure 2).

<table>
<thead>
<tr>
<th></th>
<th>$A$</th>
<th>$B$</th>
<th>$C$</th>
<th>$D$</th>
<th>$D1$</th>
<th>$D2$</th>
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<td>Physical length [m]</td>
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<td>0.536</td>
<td>1.34</td>
<td>1.70</td>
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<tr>
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<td>Physical length [m]</td>
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<td>Close injector – BOTTOM</td>
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<td>1.34</td>
<td>0.052</td>
<td>0.264</td>
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Experimental technique and post-processing

Two different lines bring water and air to the setup, respectively from a pressurized vessel (4-7 bar) and a compressor. They are equipped with flow meters in order to regulate the flow mass rate of air and the water flow rate.

Three sets of experiments were conducted:
- Far Injector
- Close Injector:
  - Top Injection
  - Bottom Injection

For the first set, the water injection point is located far from the upstream side branch. The gas velocity was varied between $U_{SG} = 10$ and 20 m/s at constant liquid rate up to $U_{SL} = 0.022$ m/s ($1.1 \times 10^{-5}$ m$^3$/s). Note that $U_{SG} = 4Q_G/(\pi D_{mp}^2)$ and $U_{SL} = 4Q_L/(\pi D_{mp}^2)$. In this operating range, the flow is expected to be stratified or stratified wavy. Indeed, depending on the combination of the superficial liquid and air velocities, the distribution of a fully developed flow along the cross sectional area of the pipe can vary. Figure 3 shows what it would be seen in a smooth horizontal pipe with an inner diameter of 1 inch.

Concerning the two Close Injector configuration test sets, the injection point is located $2D_{mp}$ from the upstream side branch. Liquid was injected using 4 small straws (ID = 1 mm) combined in a plane attached to the inner pipe wall. In this way a thin film could be generated (see Figure 4b and Figure 4c). For both sets, a first test series with dry gas is performed to obtain the gas velocity corresponding to the pressure pulsation maximum. At that fixed superficial gas velocity, the water injection rate was increased up to the full elimination of pressure pulsations. This last procedure was also repeated for slightly higher and lower gas velocities to investigate the influence of liquid injection on the condition for maximum pulsation level.

For all the experiments, dynamic pressure measurements are conducted with two flush-mounted piezometric sensors (PCB Piezotronics Pressure Division) type 116A located at the closed end of the two side branches.

The software DEWESoft 6.6.5 (DEWESoft) is used to store the data and the FFT (Fast Fourier Transform) is used to post-process the pressure measurements (30 seconds time signal) and to obtain the acoustic whistling characteristics. In the following, from the power spectrum obtained with the FFT, the amplitude peak value of the pressure pulsations is considered.

In addition, to monitor the behavior of water, two dewe-cam-fw-70 cameras are used. Particularly, Camera 1 is initially used to have a visualization of the water distribution along the longitudinal direction of the main pipe (Figure 5). For the Close-Top injector it is located next to Camera 2 to observe the behaviour of the liquid film. Camera 2 is instead used only for the experiment with Close-Top Injector to check whether any water accumulation occurs at the edges of the Tee and whether water bypasses or spans the mouth together with the shear layer. Figure 5 shows the locations of the two cameras.
FLOW VISUALIZATIONS RECORDINGS

In this section, for the first two experimental test sets, snapshots taken from the recording videos are provided at different water injection rates and discussed.

Concerning the first series with the injector far upstream, Figure 6 depicts the flow at the (upstream) T-junction. Particularly for the superficial gas velocity which corresponds to the pressure pulsation maximum ($U_{SG} \approx 15$ m/s), Figure 6 shows the behavior of the liquid film at different increasing injection rates. For the peak velocity of $U_{SG} \approx 15$ m/s the maximum expected hold-up at $Q_L = 1.1 \times 10^{-5}$ m$^3$/s is approximately 2%. Note that the hold-up is the ratio of the pipe cross-section occupied by the liquid phase to the total cross-sectional area.

From the visualizations, it is clear that, at higher liquid rates, the liquid hold-up (film height) increases. The flow regime is completely stratified with no or limited entrainment. At the highest injection rates, water starts being entrained in the gas flow. This behavior was expected, being in line with the flow pattern map (see Figure 3).

For the test with Close-Top injection, two cameras have been used: respectively Camera 1 is used to monitor the liquid film behavior, while Camera 2 is positioned to observe the film through the side branch.

Figure 6. Tandem configuration, far injector. Flow visualizations at the upstream T-junction for different liquid volumetric flow rate $Q_L$ and No Slip Liquid Volume Fractions $\lambda$: (a) $Q_L = 1.1 \times 10^{-5}$ m$^3$/s, $\lambda = 1.46 \times 10^{-4}$; (b) $Q_L = 1.9 \times 10^{-6}$ m$^3$/s, $\lambda = 2.53 \times 10^{-4}$; (c) $Q_L = 4.2 \times 10^{-6}$ m$^3$/s, $\lambda = 5.59 \times 10^{-4}$; (d) $Q_L = 6.9 \times 10^{-6}$ m$^3$/s, $\lambda = 9.19 \times 10^{-4}$; (e) $Q_L = 1.1 \times 10^{-5}$ m$^3$/s, $\lambda = 1.46 \times 10^{-3}$). The superficial gas velocity is the one corresponding to the peak. The air/water mixture flows from right to left.

Figure 5. Location of cameras.
EXPERIMENTAL RESULTS

The results of the three test sets are discussed in three different sub-sections. First, the results obtained with the far injector are discussed followed by the close injector results.

The pressure pulsation amplitude is made dimensionless by using the superficial gas velocity, the constant (gas) density \( \rho \) of 1.2 kg/m\(^3\), and the speed of sound \( c_0 \) equal to 343.2 m/s. The Strouhal number is calculated by using the diameter of the side branch \( D_b \) and the superficial gas velocity \( U_{SG} \).

Only the pressure amplitudes measured at the closed end of the downstream T-junction are hereby reported.

RESULTS – FAR Injector

Dry gas

The single phase results show a Strouhal number of \( Sr = 0.52 \) and a peak amplitude of 121 Pa. Figure 8 shows the measured pressures at the ends of the side branches. From 30-seconds time signals, the amplitude peak is considered by doing the FFT.

![Figure 8. Tandem configuration, Far injector, dry gas: pressure pulsation amplitude as function of the superficial gas velocity.](image)

The Strouhal number is higher than measured in the 2” experiments (Sanna and Golliard, 2014b) in which a Strouhal number of 0.42 was found. The difference can be attributed to the increase in the diameter ratio \( \delta \) (Ziada and Shine, 1999). While \( \delta \) is now unitary, in the 2-inch experiments of 2014 (Sanna and Golliard, 2014b) this ratio was equal to \( \delta = 0.83 \). In terms of amplitudes, they are in line with the source strengths.

The peak amplitude is 80% lower than measured values in the 2”. In the previous experiments a non-dimensional value of \( \frac{p}{\rho U_{SG} c_0} = 0.1 \) was measured, while in the current setup only a value of 0.02 is measured.

Figure 7. Tandem configuration, Close-Top injector. Flow visualizations at the upstream T-junction for different liquid volumetric flow rate \( \dot{Q}_L \) and No Slip Liquid Volume Fractions \( \lambda \). (a) \( \dot{Q}_L = 1.7x10^{-7} \text{ m}^3/\text{s}, \lambda = 2.46x10^{-5} \); b) \( \dot{Q}_L = 1.1x10^{-6} \text{ m}^3/\text{s}, \lambda = 1.59x10^{-4} \); c) \( \dot{Q}_L = 2.5x10^{-6} \text{ m}^3/\text{s}, \lambda = 3.62x10^{-4} \); d) \( \dot{Q}_L = 2.7x10^{-6} \text{ m}^3/\text{s}, \lambda = 3.91x10^{-4} \); e) \( \dot{Q}_L = 3.0x10^{-6} \text{ m}^3/\text{s}, \lambda = 4.34x10^{-4} \). The superficial gas velocity is the one corresponding to the maximum amplitude (\( U_{SG} \approx 14 \text{ m/s} \)). The air/water mixture flows from right to left. Left photos for Camera 1, Right photos of Camera 2.

Relevant information can be extracted only by looking at the frames recorded by Camera 1 (Left side) and by Camera 2 (Right Side) (Figure 7). Especially at low injection rates, it was rather difficult to align the liquid film to the main pipe axis and be sure that liquid was at the upstream edge of the T-junction. However, Figure 7 depicts a different behavior of the film depending on the amount of liquid injected. The first noticeable physical feature is that at higher injection rates the film width increases and the liquid is better aligned to the upstream side branch edge. Moreover, water bypasses the side branch mouth up to a liquid rate of \( \dot{Q}_L = 2.5x10^{-6} \text{ m}^3/\text{s} \). At higher rates, liquid is transported partly via droplets through the shear layer.
Wet gas

In Figure 9, the pulsations measured at the downstream side branch are plotted as function of gas velocity for different liquid volumetric flow rates.

The peak amplitude decreases with increasing liquid rate. The same behaviour was observed in the 2-inch pipe at low injection rates (Sanna and Golliard, 2014b). In both sets of experiments, the flow regime was stratified or stratified wavy.

Figure 11 finally shows the non-dimensional pressure as function of the Strouhal number. The Strouhal number is calculated by using the diameter of the side branch $D_{sb}$ and the superficial gas velocity $U_{SG}$. For dry gas, the peak Strouhal number is equal to $Sr = 0.522$. At liquid injection, the peak Strouhal number increases slightly to $Sr = 0.54$. At higher injection rates, this Strouhal remains constant.

**RESULTS – CLOSE Injector – Top Injection**

The injection point is now located at the top of the main pipe, 2 diameters $D_{mp}$ upstream from the upstream edge of the upstream side branch. Further details of the experimental technique are provided in Section Experimental technique and post-processing (Figure 4b). In this set of experiments, the pressure transducer of the upstream T-junction was replaced by a transparent close end, enabling the camera to see through the side branch.

Dry gas

In the first series, only the superficial gas velocity was varied. These tests aimed at finding the superficial gas velocity which corresponds to the pressure pulsation peak.

Figure 12 shows that the peak of 121 Pa is at the superficial gas velocity equal to 14.1 m/s. The pulsation amplitude measured is similar to the pulsation peak of the Far Injector configuration, whose results are reported in Figure 11. Therefore, although the velocity at which the peak occurs is 8% lower than the previous experiment, the amplitudes measurements do not seem to be affected by the supposedly intrusive effects of the injector, installed just 2 $D_{mp}$ upstream the upstream edge of the T-junction.
At the specific superficial gas velocity equal to \( U_{SG} = 14.3 \text{ m/s} \) \( (Q_G = 7.0 \times 10^{-3} \text{ m}^3/\text{s}) \), the liquid injection rate was varied. The same procedure has been adopted also for superficial gas velocities around the one of the pulsations peak, aiming at investigating the behavior of pulsations in the surroundings of the peak.

A decrease of the pulsation amplitude with increasing injection rates is observed in Figure 13. Particularly, for liquid volumetric flow rates larger than \( Q_L = 2.5 \times 10^{-5} \text{ m}^3/\text{s} \), the amplitude collapses from 60 to 20 Pa. This 60% drop is due to the presence of liquid in the shear layer. As explained and shown in Figure 7, liquid stopped bypassing the mouth and starts to interfere with the shear layer, i.e. the hydrodynamic instability which generates sound.

In addition, after eliminating pulsations, the liquid rate was reduced to \( 2.3 \times 10^{-5} \text{ m}^3/\text{s} \) and a clear hysteresis can be observed.

**RESULTS – CLOSE Injector – Bottom Injection**

The results presented in the following are obtained with the injection point located at the bottom of the main pipe and \( 2 \text{ D}_{mp} \) upstream the upstream side branch (see Figure 2 and Figure 4c).

**Dry gas**

A first test with dry gas aimed at disclosing the pressure pulsations peak and the corresponding superficial gas velocity. This was found equal to 15.3 m/s, similarly to the one of the **Far injector** configuration. On the other hand, Figure 14 shows the pressure amplitude is about the 30% lower. This difference in amplitude could be due to the obstruction generated by the injector. Nevertheless, the Strouhal corresponding to the pulsation peak is equal to 0.52, the same reported in Figure 11.

A decrease of the pulsation amplitude with increasing injection rates is observed in Figure 13. Particularly, for liquid volumetric flow rates larger than \( Q_L = 2.5 \times 10^{-5} \text{ m}^3/\text{s} \), the amplitude collapses from 60 to 20 Pa. This 60% drop is due to the presence of liquid in the shear layer. As explained and
The results obtained with a superficial gas velocity of 15 m/s at different injection rates (0, 150 ml/min, 250 ml/min and 350 ml/min). The results obtained with a superficial gas velocity of 15 m/s at different injection rates as function of the varying frequency are particularly interesting, being the superficial gas velocity of the experiments hereby discussed in the range between 13 and 16 m/s. Only experimental results up to the ratio of $Q_L/Q_G$, equal to 0.02% are provided. With a crude approximation, the expected damping behavior could be extrapolated to have a potential estimate even at higher $Q_L/Q_G$ ratios (see Figure 17).

1D acoustical simulations have been run with the same source at the Tees and different damping values varied only in the middle distance B. The values are the ones extrapolated by using the experimental results of Golliard et al. (2013), calculated for the 1-inch pipe. Note also that the damping estimated with the Kirchhoff law for the 1-inch pipe is around...
0.046 l/m. From the comparison shown in Figure 18 it is possible to see that the experimental results obtained in the three sets and the ones of the 1D simulations are in agreement. As the acoustical field in the upstream and downstream segments (A and C, see Figure 2) of the setup is very weak, the damping in these segments does not affect the pulsation level. This was confirmed by our model.

![Figure 18. Comparison between the experimental results and the 1D acoustical model.](image)

Based on this estimation, the main decrease in pulsation amplitude is attributed to the additional damping in the B section pipe. However, predictions of the additional acoustic damping due to the liquid are quite uncertain and therefore, further investigations on damping are needed. The acoustic damping in presence of water is the subject of a follow-up experimental study to determine whether the assumptions made (and particularly the extrapolation of Figure 17) are reasonable.

**CONCLUSIONS**

Depending on the combination of superficial gas and liquid velocities, the annular flow pattern can occur, typically characterized by a liquid film at the pipe wall.

For the tandem configuration, the interaction between the liquid film and the shear layer generated at the upstream edge of each T-junction was thought to be the reason of the pressure amplitude decrease reported in previous experimental investigations.

To evaluate the FIPs trend as function of that liquid film at the top of the main pipe, three sets of experiments have been conducted. Firstly, the water injection point has been located around 68 diameters upstream the upstream T-junction. Secondly, the injection point was moved to 2 diameters upstream the side branch, first generating a film of water only at the top of the main pipe, later only at the bottom.

The results obtained show that the pressure pulsations trend is not significantly changing while varying either the distance of the injection point from the upstream side branch or the different location in the cross sectional area. From flow visualizations it seems that for the closer top injection a large drop in pulsations amplitudes occurred only if water is convected together with the shear layer. Nevertheless, the pressure amplitude decrease (typically observed in annular flow patterns) cannot be only due to the presence of the liquid film at the top of the main pipe.

It is likely that extra damping due to the presence of water is a good candidate for explaining the reduction in pulsation amplitude.

**ACKNOWLEDGMENTS**

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