Air-Water Drainage Flow through Finned Bend

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Abstract
This experimental study examines the two phase flow structures of airflow pressures for annular flow through a 90° bend, with and without, a vortex fin for drainage applications. The superficial liquid flow characteristics: Reynolds number ($Re_L$) and air-to-water flow volume ratio (AW) in the ranges of 11200-20000 and 1.1 - 9.6 respectively were selected as the control parameters throughout the specified tests. At each test condition the flow structures observed by the computerized videography were also synchronized to the airflow pressure measurements. Particular dependence on $Re_L$ and AW, the interfacial air-water flow behaviour through the 90° bend with and without a vortex fin varied periodically, to generate a variety of two-phase patterns which signified the temporal airflow pressure variations. The associated flow physics of the dynamic processes of airflow pressure variations were then revealed. In the 90° bend with fin, the down-flow water screen was discontinuous, leading to a reduction of positive airflow pressure. The empirical correlations observed permitted the individual interdependent evaluation of $Re_L$ and AW impact on the time-mean airflow pressures in the 90° bend with and without a vortex fin were derived to assist the design performance.

Keywords: drainage; stack bend

1. Introduction
A drainage system is generally constructed by a vertical stack that is interconnected by tilted horizontal branches to discharge air-water flows from a variety of terminal appliances. Air can entrain into the horizontal branches and form a stratified or wavy air-water flow which directs toward the branch junction connected to the vertical stack. This air-water flow at the branch junction can impinge on the opposite stack wall where the discharge separates and spreads around the vertical stack to induce swirls. A downward annular water flow is rapidly established in the vertical stack. Upstream of the annular flow in the vertical stack, the airway is intermittently blocked by the water screen on either side and below the branch discharge, Swaffield and Campbell (1995). In an extreme condition, the stoppage of a moving airflow at high velocity can cause severe pressure surges that can damage the trap seal. As the branch discharge is a random and intermittent event, the stratified-wavy flow in the horizontal branch combined with the annular flow in the vertical stack, are both a transient phenomena, Swaffield and Campbell (1992). Locally positive or negative transient airflow pressures are accordingly developed and propagate through the drainage system. One of the primary functions of a drainage system is to prevent foul odours entering habitable spaces through the interconnected drainage network; the water seal in each trap must be protected. Studies that analyzed the pressure surge propagation in a drainage system along with the suppression and control of the pressure surge propagation were accordingly performed, Swaffield and Campbell (1995), Swaffield and Campbell (1992), Warfield et al. (2004), Swaffield (2006). The transient propagation of the pressure surge in a drainage system is affected by the local interfacial flow structures and the reflection and transmission of the pressure waves at the flow boundaries; which combine to generate complex two-phase flows to signify the characteristics of the particular drainage system. The positive or negative transient pressures in the stack and branch; which interdependently alter the interfacial flow structure and the airflow velocity; can possibly damage the trap seal, causing unfavorable acoustic effects and limit the maximum discharge capacity of a drainage system.

While the blockage of stack due to the branch discharge causes a positive pressure transient in the...
dry stack above this branch, the accelerated downward airflow induces local pressure reduction in the downstream stack by converting its pressure potential into kinetic energy. The downstream pressure from the branch junction in the vertical stack continuously decreases until the air-water flow approaches the final bend through which the downward annular flow re-directs into the horizontal discharge manifold. An intermittent down fall water curtain can be formed at the location of the downstream or the bend. With the local void fraction approaching zero at the water curtain location, the airflow is stopped with the high positive pressure transient generated in a cyclic manner. The sudden blockage of airflow through the final bend triggers a severe transient pressure excursion which influences the upstream pressure recovery that elevates the regional sub-atmospheric pressure into a positive pressure at the lower end of the vertical stack. As the transient flows in the branch junctions and stack are interdependent, the pressure transients affected by the two-phase flow phenomena associated with each component can modify the pressure distribution along the stack. Dominant among these is the pulsating pressure wave located in the final bend of the stack.

It is not clear why the interfacial flow structure located at the bend is a transitional flow regime from the annular entry flow to the stratified exit flow, while, the temporal and spatial pressure variations through an elbow bend from the vertical-down to horizontal pipes must be given careful consideration at the design stage of the drainage system. As summarized by Spedding and Benard (2007), studies on the two-phase flow in curved pipes have largely been confined to horizontal planes, thus leaving out the effect of gravity on these particular flow regimes. Having considered the effect of bend orientation and the contrary results between: horizontal, horizontal-to-vertical up, vertical-down to horizontal bend were reported. Spedding and Benard (2007). Peshkin (1961) reported that the pressure drop for the air-water flow through the bend with horizontal to vertical-down flow increased about 10% from the result obtained with the horizontal to vertical-up bend flow. Spedding et al. (2000) also discovered that slight interfacial disturbances across the vertical pipe could lead to an increase in pressure drop due to the increased liquid hold up and semi-blockage. As the air slugs tend to be of shorter length, resulting in a narrower but increased frequency of pressure fluctuations in the vertical pipe connecting with an elbow bend, the liquid holdup thus becomes higher in the vertical pipe with an elbow bend, leading to increased pressure drop. Particularly, when the air-water stream flows through a curved channel, the induced centrifugal force acts as an additional body force on the gaseous and liquid flows to affect the interfacial structures. Kirpalani et al. (2008) has reported the flow morphology for air-water flows through curved tubes. With the inertial and viscous forces dominating the flow physics in the curved tube, the liquid-phase tends to shift towards the tube wall and agitates the onset of intermittent flow to enhance the phase interaction. Relevant research works concerned with annular air-water flow through a vertical-down to horizontal bends are uncommon, with insufficient experimental data results to substantiate and clarify relevant intermittent air-water two-phase flow phenomena for drainage applications. Very limited passive measurements have been reported in the open literature with an attempt to alleviate the intermittent pressure surge generated at the final bend of a stack, Swaffield (2006). By fitting a vortex fin on the upper wall of the bend to break the down fall of water screen in the bend, the blockage of airway due to water curtain is moderated so that the degree of temporal pressure surge can be reduced. This study makes a comparative examination of the two-phase flow structures; the spatial and temporal pressure variations and the time-averaged airflow pressures detected with plain and two-finned vertical-down horizontal 90° bends. Experimental conditions were controlled by the air-to-water volume flow ratio (AW) and Reₖ for both plain and finned bends. For the drainage application the positive pressure surge developed in the final bend of the vertical stack certainly serves as the primary point of interest, with two sets of empirical data correlations evaluating the time-averaged pressure surges in the plain and the two finned bends.

2. Experimental Facility and Program

Fig.1.(a) depicts the experimental facility, which consists of an air-water mixer (1), a 2m long developing section (2), a 90° vertical-down to a horizontal test bend (3) and a 290mm horizontal discharge pipe (4). The complete test apparatus is assembled into a seamless and transparent pipeline with an inner diameter of 50mm. The origin of the streamwise coordinate system (S) is located at the exit of the air-water mixer, Fig.1.(a). De-humidified dry air is channeled into the central tube at the top of the air-water mixer. Prior to entering the air-water mixer, the volume flow rate of the airflow is adjusted and measured by the needle valve (5) and the volume flow meter (6) respectively. A digital pressure transducer (7) and a type K thermocouple (8) are used to measure the airflow entry pressure and temperature. Four entry ports with equal angular interval issue water streams into the air-water mixer, Fig.1.(a). The water flow rate fed into each entry port of the air-water mixer is individually controlled and measured by four sets of needle vales (9) and volume flow meters (10) so that the water flows entering each port of the air-water mixer can be adjusted at the same rate. The evaluation of the Reₖ entering the test bend is based on the total water flow rate fed into the air-water mixer. The length of the developing section (2) is sufficient to obtain the
air-water annular flow prior to entering the test bend. All tests are performed at approximately atmospheric pressure and are specific to $Re_L$ and $AW$ as the control parameters that governed the test condition.

Four probing tubes are equipped with pressure taps each of 0.5 mm diameter into the centroids along the test pipe to measure the local airflow pressures, Fig.1.(a). Each pressure tap is connected with a micro-manometer (11) to detect the instant airflow pressure. In order to synchronize the flow images and the instant airflow pressure measurements, the video recording system (12) filming the temporal pressure variations indicated by the micro-manometers (11) and the Computerized Digital Camera (CDC) system (12) that is capable of taking 300 snap shots per second are equipped with two synchronized chronographs. The instant flow image detected by the CDC system and the corresponding local pressure distributions measured by the micro-manometers are post processed to determine the cyclic pressure variations at each measurement location and its time-averaged pressure. The present CDC system and information processing method have been previously commissioned, Chang et al. (2009), Chang and Yang (2009). At each test condition, the video CDC and cameras are mounted on two tripods and aimed at the angles normal to the micro-manometers and the test bend respectively. These camera lenses are fixed at a constant focal length. Flow images are also scanned on-line at each test condition.

To avoid refraction image in each CDC snap shot, the locations and strengths of several light sources are adjusted.

Fig.1.(b) depicts the plain and finned vertical-down to horizontal test bends with an inner bore of 50mm. Each 90° test bend (1), with or without the vortex fin, is machined from two transparent acrylic plates. The angular coordinate system $(\theta)$ for this elbow bend is also indicated in Fig.1.(b). As referred to as the vortex fin in Fig.1.(b), the divergent pyramid is bent and machined to match the upper contour of the bend at $\theta = 45^0$ or $55^0$. A pair of semi-circular divergent grooves is machined on the two inclined sidewalls of each vortex fin. The diameters of each divergent groove vary linearly along the vortex fin from 3.1mm (leading) to 10mm (trailing). As the water film traverses the vortex fin, two water streams separate at the leading edge of the vortex fin and are then guided into the semi-circular grooves within which these water streams turn into a pair of counter-rotating vortices so that the downstream coalescence of these two separated water streams can be avoided. This vortex fin is designed to break the water curtain formed in the bend of a stack. The length of the vortex fin is 25mm with a height of 5 and 12.5mm at the leading and trailing edges respectively, giving a tapered angle of 16.7 degrees. The widths at the leading and trailing edges of the vortex fin are 6.2 and 15mm respective to constitute an inclined angle of 20 degrees. The vortex fin is individually machined and glued on to the upper wall of the bend at $\theta = 45^0$ or $55^0$.

The experiments are conducted under the test pressures in the range of 1-1.15 bars. $Re_L$ is evaluated from the superficial liquid velocity $(V_{SL})$ and the diameter of the test bends $(D)$. For each test bend, the flow visualizations and pressure measurements are simultaneously performed with five different AW at each tested $Re_L$, namely 11200, 13500, 15800, 18000 or 20000. The test AW and $Re_L$ ranges ensure the annular air-water flow in the vertical pipe. The superficial gas $(V_{SG})$ and liquid $(V_{SL})$ velocities fall in the ranges of 0.24-2.03 and 0.21-0.38 $ms^{-1}$ respectively. The comparisons of the synchronized flow images and pressure measurements detected from the plain and finned bends reveal the impact of the vortex fin and its allocation on the interfacial structures and pressure variations through the vertical-down to horizontal bend. Having acquired the instant pressure data at each measurement location, the time-averaged pressures at a set of tested AW and $Re_L$ are individually determined for the plain and finned bends. The varying ratios of the time-averaged pressures ($P_{Fin}/P_{Plain}$) and the ratios for the amplitudes of the oscillating pressure waves ($\alpha_{Fin}/\alpha_{Plain}$) between the plain and finned elbow bends against AW at each tested $Re_L$ are subsequently examined. A regression type analysis to derive the time-averaged pressure correlations for the plain and
the two fined bends is also conducted. Estimations of the experimental uncertainties for the present measurements are conducted, ASME JHT Editorial Board (1993). The precision of the micro-manometer measuring the instant airflow gauge pressure ($P$) is 9.8 Nm$^{-2}$. With the fluid temperatures in the range of 293-297K and the instant pressure measurements between 430-3920 Nm$^{-2}$, the maximum uncertainties for $P$, $Q_a$, $Q_w$, $\alpha$ and $Re_L$ are about 2.3%, 1.2%, 1.1%, 5.3% and 3.2% respectively.

3. Results and Discussion

The transition of interfacial air-water flow structures from the annular to stratified flow in the plain and finned bend appears as a dynamic process with complex periodic patterns. This is demonstrated by a set of snap shots which depict the instant flow images taken from each test bend in a sequential order, Fig.2.

The temporal variations of the airflow pressures at the central core on the sectional plane of $\theta$ = 45° in (a) plain (b) finned ($\theta$ = 45°) (c) finned ($\theta$ = 55°) bends, along with the corresponding synchronized flow images through these bends are compared in Fig.2. at $Re_L$=15800, AW=2.85. The synchronized interfacial air-water flow structures and the airflow pressures in Figs.2.(a), 2.(b), 2.(c) depict the process of interfacial transition over a complete cycle. However, although the sequential display of the ten flow images from A→J in each plot of Fig.2. can characterize the cyclic flow patterns in each test bend, the period for each cycle, the detailed temporal variations of the airflow pressure and its associated flow image vary slightly; indicating the highly unstable flow fields in each bend. In the plain bend, the cyclic variations of air-water interfacial structures result in the cyclic airflow pressure variations, Fig.2.(a). As indicated by snap shot A in Fig.2.(a), the down-fallen water annular film appears in a form of the dispersed water screen through the bend. Driven by the streamwise flow inertia, this dispersed water screen is sequentially evolved into the falling water screen (snap shot B), the splashing water screen (snap shot C) and the water curtain (snap shot D). This water curtain is unstable and is soon disrupted to produce an explosive pressure wave that triggers the downstream water surge to induce the stratified wavy flow in the horizontal pipe (snap shot E). The peak airflow pressure is accordingly generated at the instant of water-curtain disruption. The downstream convection of the wavy water surge is then disrupted (snap shot F) after which the airflow pathway is gradually cleared and causes the continuous P reduction from G → I, Fig.2.(a). Followed by the downstream convection of the disrupting water surge, the stratified water wave in the horizontal pipe is eventually disrupted (snap shot J). The cyclic air-water interfacial process, (snap shots A → J) as well as the oscillating airflow pressures, repeatedly occurred. By fitting a vortex fin at the location of $\theta$ = 45°, the snap shots B → J in Fig.2.(b) clearly demonstrate the separations of water screen into the downstream swirls after the vertical water annular film encounters the vortex fin (snap shot A). Unlike the plain bend with the severe periodic airway blockage due to the formation of the water curtain, the amplitudes of the periodic pressure waves are considerably moderated in the finned bends, Fig.2. The stratified water surge in the horizontal pipe downstream of each finned bend is consequently weakened, snap shots A → E in Fig.2.(b). However, the water surge on the bottom half of the finned elbow bend due to the decelerated water flow by the increased friction and pressure drags at the bend also appears as a dynamic process and remains unavoidable, snap shots F → I in Fig.2.(b). Although the water surge at the bottom half of the bend can be periodically collapsed as seen in snap shot J in Fig.2.(b), the presence of the vortex fin along with the water surge on the bottom half of the bend partially choke the airway to produce a pressure peak between the instants F to I. In order to moderate the aforementioned choking effect in the finned elbow bend, the location of the vortex fin is shifted downstream to $\theta$ = 55°. As demonstrated by Fig.2.(c), the vortex fin at $\theta$ = 55° can still effectively separate the incoming water film into downstream swirls. The dynamic variations of the interfacial air-
water structures in the finned bend of $\theta = 55^\circ$ still follow those observed in Fig.2.(b); but the water surge seen in Fig.2.(c) at the bottom half of the finned bend ($\theta = 55^\circ$) is suppressed, Fig.2.(b). This result is an indication of the reduced airway choking by shifting the vortex fin from $\theta=45^\circ$ to $55^\circ$. As a result of the moderated choking effect in the finned bend of $\theta=55^\circ$, the instant airflow pressures depicted by Fig.2.(c) are further reduced from those in the finned bend of $\theta=45^\circ$. However, when air flows through the bend, Dean-type vortices are generated by the centrifuge force. Such re-circulating vortical airflow structures on the sectional plane of each bend interacts with the water film to preserve the $Re_L$-dependent minimum airflow pressures at the limiting conditions of $AW=0$. This will be demonstrated in the later section.

Fig.3. compares the streamwise distributions of airflow pressure from the vertical to horizontal pipes through the $90^\circ$ plain and finned bends at $Re_L=15800$ with $AW= (a) 0 \ (b) 2.85 \ (c) 4.57 \ (d) 5.71$.

In each plot of Fig.3., the time-averaged pressure ($\bar{P}$) at each measurement location for each set of tested $Re_L$ and $AW$ is averaged from 20 pressure waves and marked with the averaged oscillating amplitude ($\alpha$). Depending on the profile of each temporal pressure variation, $\bar{P}$ at each measurement location is not necessary at the middle of each $\alpha$ span, Fig.3. At $AW=0$ for a drainage system, the shearing action on the air-water interface entrains airflow to the discharge, leading to the sub-atmospheric pressures over the bottom stack. This is demonstrated by Fig.3.(a) in which the local airflow pressures over the detected region along the three pipelines with the plain, or two finned bends are sub-atmospheric. Also, noteworthy as shown in Fig.3.(a) are the vanished $\alpha$ spans at each location along all three test pipes. Clearly, the driven force by the water film is not sufficient to create a complete vacuum situation in each test pipe; while these sub-atmospheric levels vary among the three test pipes due to the different hydrodynamic characteristics, Fig.3.(a). In this respect, the pressure values in the test bend of $\theta=55^\circ$ at $Re_L=11200$ with $AW=0$ are slightly higher than the atmospheric level, indicating the development of the re-circulating airflow cells as the obstacle to entrainment.

A review of the entire flow images at $AW=0$ confirms that while the hydrodynamic transition of the water flow in each test bend follows the process detected at the two-phase condition ($AW\neq0$) the degree of water surge is considerably moderated. Upstream of these test bends, the sub-atmospheric magnitudes are influenced by the flow structures in each bend and follow the order of finned bend ($\theta=55^\circ$) < plain bend < finned bend ($\theta=55^\circ$), Fig.3.(a). In each test bend at $AW=0$, the pressure levels are further reduced but soon recovered after traversing each test bend. The weakened airflow at $AW=0$ condition considerably moderates the air-water interfacial interactions over the flow region upstream of each test bend. With the presence of the airflow at $AW>0$, the oscillating pressure waves initiated from each test bend exert considerable upstream impacts on the airflow pressures in the vertical pipe, Figs.3.(b)-(d). The $\alpha$ spans are observed at each measurement location along the test pipeline for all the two-phase test conditions, Figs.3.(b)-(d). The time-averaged local airflow pressures as well as the $\alpha$ spans along the pipeline with the finned bend of $\theta=55^\circ$ are consistently less than their comparative counterparts, Figs.3.(b)(c)(d). At $AW=5.71$, the airflow pressures in the pipeline with the finned bend of $\theta=45^\circ$ exceed their plain-bend counterparts due to the severe choking effects at the bend throat, Fig.3.(d). In general, the amplitudes of the pressure waves developed in the bends follow the order of plain bend > finned bend ($\theta=45^\circ$) > finned bend ($\theta=55^\circ$). Contrary to the pressure drops at the throat of each test bend as $AW=0$ in Fig.3.(a), the time-averaged airflow pressures and their accompanying $\alpha$ spans are amplified at the throat as $AW>0$ in Figs.3.(b)-(d) due to the intermittent airway blockages.

To highlight the influence of vortex fin on $\bar{P}$ at the throat of each test bend, the variations of $\bar{P}_{\text{fin}}/\bar{P}_{\text{plain}}$ against $AW$ at fixed $Re_L$ for the finned bends are collected in Fig.4. As the vertically fallen water film can be diverted into downstream vortex streams, the increase of $\bar{P}$ due to the sudden airway blockage by the water curtain can be avoided. However, the vortex fin also acts as a blocking object in the airway so that the location of the vortex fin can vary the $\bar{P}$ and/or $Re_L$-driven $\bar{P}$ variations.

At $AW=0$, the presence of the vortex fin in the airway undermines the airflow entrainment so that the sub-atmospheric pressures in each finned bend are considerably moderated from the plain-bend counterparts. In the fin bends of $\theta= 45^\circ$ and $55^\circ$, $\bar{P}_{\text{fin}}/\bar{P}_{\text{plain}}$ can be respectively reduced to the ranges of 0.37-
the beneficial fin effect on suppressing the fin. Further increase of P present in the plain bend at due to the air-water interfacial mechanism is weakly mechanism and the fin blockage. When the bend reflects the combined effect of the interfacial mechanism in the plain bend, the P\(_{\text{fin}}\)/P\(_{\text{plain}}\) turns into a weak function of Re\(_t\) in the finned bend of \(\theta = 55^0\), Fig.4(b).

To develop the empirical correlations using AW and Re\(_t\) as the controlling parameters, the time-averaged airflow pressure and the oscillating amplitude of the pressure wave are respectively expressed in the dimensionless forms as P\(^*\) and \(\omega\)/D where P\(^*\) is converted from the P detected at the bend throat as P/\((\rho gD)\). Fig.5. depicts the variations of P\(^*\) against AW at each tested Re\(_t\) for (a) plain (b) finned (\(\theta =45^0\)) (c) finned (\(\theta =55^0\)) bends.

For all the Re\(_t\) tested with AW>0, P\(^*\) consistently increases as AW increases at each tested Re\(_t\). At a selected AW, the collective data trends in each plot of Fig.5. suggest that P\(^*\) increases as Re\(_t\) increases. However, the review of the P\(^*\) data generated at AW=0 conditions reveals that these P\(^*\) obtained at AW=0 decrease as Re\(_t\) increases. Such data trend is not distinguishable along the ordinate of Fig.5. due to the scaling difficulty. But this particular result indicates the enlarged sub-atmospheric level due to the enhanced airflow entrainment by increasing the mass flux of the water flow at AW=0. Confirmed by the AW driven linear increasing trend for P\(^*\) at each tested Re\(_t\) in each plot of Fig.5., P\(^*\) can be correlated as A + B × AW in linear increasing trend for P\(^*\) at each tested

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\frac{P_{\text{fin}}}{P_{\text{plain}}} \text{ to less than unity for the finned bend of } \theta = 45^0, \text{ Fig.4(a). Nevertheless, a downstream shift of the vortex fin from } 45^0 \text{ to } 55^0 \text{ weakens the fin effect on the airway blockage at the bend throat; but enlarges the P dependency on the interfacial mechanism. As a result, } P_{\text{fin}}/P_{\text{plain}} \text{ turns into a weak function of } Re_t \text{ in the finned bend of } \theta = 55^0, \text{ Fig.4(b).}
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\text{Fig.4. Variations of } \frac{P_{\text{fin}}}{P_{\text{plain}}} \text{ at Bend Throat Against AW at Fixed } Re_t \text{ for the Test Bends with Vortex Fin at } \theta = (a) 45^0 \ (b) 55^0 \text{ respectively).}
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0.85 and -0.15-0.13, Fig.4. Nevertheless, while P remains negative for the plain or finned (\(\theta =45^0\)) bends at the AW=0, the P becomes positive in the finned bend of \(\theta =55^0\) at Re\(_t\)=11200 when the entraining power is relatively weak, leading to negative P\(_{\text{fin}}\)/P\(_{\text{plain}}\) for the finned bend (\(\theta =55^0\)), Fig.4.(b). In the Re\(_t\) and AW ranges of 11200-20000 and 1.1-9.6, P\(_{\text{fin}}\)/P\(_{\text{plain}}\) varies between 1.039-0.951 and 0.874-0.901 for the finned bends of \(\theta = 45^0\) and \(\theta = 55^0\) respectively, Fig.4. For the finned bend of \(\theta = 45^0\) or \(\theta = 55^0\), P\(_{\text{fin}}\)/P\(_{\text{plain}}\) appears as a weak function of AW at each tested Re\(_t\), indicating the similar degree of AW impacts on P in the plain and finned bends. While the P\(_{\text{fin}}\)/P\(_{\text{plain}}\) obtained with various Re\(_t\) from the finned bend of \(\theta = 55^0\) tend to converge into a tight data band in Fig.4.(b), P\(_{\text{fin}}\)/P\(_{\text{plain}}\) noticeably decreases as Re\(_t\) increases for the finned bend of \(\theta = 45^0\). This result reveals the different degrees of Re\(_t\) impacts on P between the plain and finned (\(\theta = 45^0\)) bends. At relatively low Re\(_t\), the air-water interfacial variations remain relatively weak with moderate P surge caused by the water curtain in the plain bend. However, along with the hydraulic jump which causes the water surge at the bottom throat of each test bend, the airway blockage caused by the vortex fin at \(\theta = 45^0\) constantly adds the choking effect. While the P surge solely depends on the air-water interfacial mechanism in the plain bend, the P surge in the finned bend reflects the combined effect of the interfacial mechanism and the fin blockage. When the P surge due to the air-water interfacial mechanism is weakly present in the plain bend at Re\(_t\) less than 15800, the P\(_{\text{fin}}\)/P\(_{\text{plain}}\) for the bend of \(\theta = 45^0\) become higher than the unity in Fig.4.(a) due to the added airway blockage by the fin. Further increase of Re\(_t\) from 15800 amplifies the beneficial fin effect on suppressing P and leads P\(_{\text{fin}}\)/P\(_{\text{plain}}\) to less than unity for the finned bend of \(\theta = 45^0\), Fig.4(a). Nevertheless, a downstream shift of the vortex fin from \(45^0\) to \(55^0\) weakens the fin effect on the airway blockage at the bend throat; but enlarges the P dependency on the interfacial mechanism. As a result, P\(_{\text{fin}}\)/P\(_{\text{plain}}\) turns into a weak function of Re\(_t\) in the finned bend of \(\theta = 55^0\), Fig.4(b).

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\text{Fig.5. Variations of Time-Averaged Dimensionless Pressure (P^*) Against AW at Each Tested Re_t for (a) Plain (b) Finned (\(\theta =45^0\)) (c) Finned (\(\theta =55^0\)) Bends}
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The varying manners of coefficients A, B against Re\(_t\) are plotted in Figs.6.(a)(b) respectively. The physical implications of coefficients A, B are the P\(^*\) levels at AW=0 and the degree of AW impact on P\(^*\) respectively.

As seen in Fig.6.(a), the increase of Re\(_t\) at AW=0 keeps reducing P\(^*\) or enlarging the sub-atmospheric levels for each test bend. The most severe sub-
Fig. 6. Variations of Coefficients (a) A (b) B Against $Re_L$ in $P^*$

Correlations (c) Comparison of Correlation Results of $P^*$ with Experimental Measurements

Atmospheric conditions, which are harmful for a drainage system, develop in the pipeline fitted with the plain bend; while the installation of the present finned bend at $\theta = 55^\circ$ offers the most favorable $P^*$ performances among the three comparative groups over the entire parametric ranges, Fig. 6.(a). As B coefficient indices the degree of AW impact on $P^*$, the similar B values for three test bends at each tested $Re_L$ as shown as Fig. 6.(b) re-confirms the similar degrees of AW impacts on $P^*$ for the three test bends. Justified by the data trends depicted in Figs. 6.(a)(b), the best fits for A, B coefficients and therefore the $P^*$ correlations are obtained as equations (1)-(3).

$$P^* = (1.8 \times 10^{-6} \times Re_L - 1.83 \times 10^{-10} \times Re_L^{0.5}) \times AW$$
Plain bend

$$P^* = (1.8 \times 10^{-6} \times Re_L - 1.7 \times 10^{-11} \times Re_L^{0.5}) + (3.31 \times 10^{-11} \times Re_L^{2.5}) \times AW$$
Finned bend ($\theta = 45^\circ$)

$$P^* = (4.19 \times 10^{-7} \times Re_L - 3.39 \times 10^{-11} \times Re_L^{2.5}) + (5.2 \times 10^{-12} \times Re_L^{3.5}) \times AW$$
Finned bend ($\theta = 55^\circ$)

As compared by Fig. 6.(c), the maximum discrepancies between the experimental measurements and the correlation results are less than $\pm 30\%$ for the entire $P^*$ data generated.

Another noteworthy aspect that is characteristic of drainage applications is the oscillating amplitude of the pressure waves ($\alpha$) developed at the throat of each test bend. The dimensionless form of $\alpha$ is defined as $\alpha/D$ and symbolized as $\alpha^*$. Fig. 7. collects the $\alpha^*$ variations against AW at fixed $Re_L$ for (a) plain (b) finned ($\theta = 45^\circ$) (c) finned ($\theta = 55^\circ$) bends. Unlike the $P$ results which reach sub-atmospheric levels and vary with $Re_L$ at AW=0, $\alpha^*$ at AW=0 for each tested $Re_L$ approaches zero. As depicted by Fig. 7., $\alpha^*$ increases as AW and/or $Re_L$ increases. Again, by each AW-driven $\alpha^*$ varying trend at a fixed $Re_L$, $\alpha^*$ can be well correlated as $m \times AW^n$ in which the m coefficient and n exponent are functions of $Re_L$.

Figs. 8.(a)(b) clearly shows the varying manners of $m$, n against $Re_L$ between the three test bends. As compared by Fig. 8.(a), the $m$ values for the two tested finned bends of $\theta = 45^\circ$ and $55^\circ$ are similar, which are considerably less than their plain-bend counterparts. The variations of n exponent with $Re_L$ for the three test bends clearly demonstrate that the AW impact on $\alpha^*$ depends on $Re_L$. By treating the n exponent as an index for the degree of interdependent AW-$Re_L$ impacts on $\alpha^*$, the n exponents for the finned bends of $\theta = 45^\circ$ and $55^\circ$ decay at a faster rate than those for the plain bend as $Re_L$ increases; although most of the n exponents for the plain bend are still lower than their finned-bend counterparts, Fig. 8.(b). Based on the n performances compared in Fig. 8.(b), the higher degree of interdependent AW-$Re_L$ impacts on $\alpha^*$ develops in the finned bends as $Re_L < 18000$ above which the interdependent AW-$Re_L$ impacts on $\alpha^*$ become similar. All the $m$, n data trends shown in Fig. 8. follow the power law. After correlating $m$, $n$ as the functions of $Re_L$ and substituting $m$, n functions into $\alpha^*$ equations to give rise to the $\alpha^*$ correlations as:

$$\alpha^* = (8.64 \times 10^{-12} \times Re_L^{3.5}) \times AW$$
Plain bend

$$\alpha^* = (4.75 \times 10^{-12} \times Re_L^{4.5}) \times AW$$
Finned bend ($\theta = 45^\circ$)

$$\alpha^* = (2.04 \times 10^{-12} \times Re_L^{5.5}) \times AW$$
Finned bend ($\theta = 55^\circ$)

The discrepancies between the experimental $\alpha^*$ measurements and the correlative results using equations (4)-(6) are compared in Fig. 8.(c). Three distinguishable data clusters indicate that the overall $\alpha^*$ values follow the order of plain-bend > finned bend ($\theta = 45^\circ$) > finned bend ($\theta = 55^\circ$). The maximum discrepancies of $\pm 30\%$ are obtained for between $98\%$ of experimental $\alpha^*$ measurements and the correlative results obtained from equations (4)-(6).

4. Conclusions

The periodic variations of the air-water interfacial structures in the plain and finned bends respectively
follow the processes of (a) fallen water screen→ (b) formation of water curtain→ (c) water curtain disruption→ (d) water surge from the bottom throat of bend→ (e) disruption of water surge in the horizontal pipe downstream of the bend; and (a) fallen water screen→ (b) separation of water screen into downstream swirls along the upper sleeve of the horizontal pipe connecting with the bend→ (c) water surge from the bottom throat of the bend→ (d) collapse of water surge at the bottom throat of the bend. In the plain bend, the airflow pressure starts rising during the formation of the water curtain and reaches the peak value at the instant of the water-curtain disruption. For each finned bend, the peak airflow pressure takes place when the water-surge at the bottom of the throat chokes at the bent airway location.

The protruding vortex fin in the bent airway suppresses the effectiveness of the airflow entrainment driven by the water flow. At \( AW=0 \), the magnitudes of sub-atmospheric pressures in each finned bend are considerably moderated from those in the plain-bend. For the finned bends of \( \theta = 45^\circ \) and \( 55^\circ \) at \( AW=0 \), \( \bar{P}_{\text{fin}}/\bar{P}_{\text{plain}} \) are respectively reduced to the ranges of 0.37-0.85 and -0.15-0.13. With \( AW>0 \), the effectiveness of the vortex fin for moderating \( \bar{P} \) at the bend throat is undermined due to the complex air-water interfacial mechanisms. With \( 11200<Re_t<20000 \) and \( 1.1<\bar{P}_{\text{fin}}/\bar{P}_{\text{plain}} \leq 0.20 \), \( \bar{P}_{\text{fin}}/\bar{P}_{\text{plain}} \) varies between 1.039-0.951 and 0.874-0.901 for the finned bends of \( \theta = 45^\circ \) and \( 55^\circ \) respectively. As \( \bar{P}_{\text{fin}}/\bar{P}_{\text{plain}} \) appears as a weak function of \( AW \) at each tested \( Re_t \), the degree of \( AW \) impacts on \( \bar{P} \) in the plain and finned bends are similar.

Three sets of \( P^* \) and \( \alpha^* \) correlations that permit the evaluation of the time-averaged pressure and the amplitude of the oscillating pressure wave for the airflow at the throat of the plain and the two finned bends are generated.

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