The behavior of bouncing jet

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Abstract. A series of experimental study was carried out with a special interest on a behavior of impinging liquid jet to a flowing bath of the same liquid. It has been known that the jet bounces from the bath against the gravity even after the penetrating to the liquid bath under a narrow range of condition. This unique behavior is often called as ‘the bouncing jet.’ Entrainment of ambient gas around the jet results in forming a thin gas layer between the jet and the liquid bath to realize a non-coalescence jet in the bath. This is a key phenomenon to understand the dynamics of the impinging liquid jet. In the present study the authors focus on this ambient gas entrainment in the system that the impinging jet penetrates to coalesce into the flowing liquid bath; especially on the evaluation of the thickness of the entrained gas around the penetrated jet.

1. INTRODUCTION

Impinging liquid jet on a flowing liquid bath can been seen in a variety of industrial applications, for example, prevention of air bubble mixing in casting process and improvement of mixture efficiency of gas-liquid/liquid-liquid system. Entrainment of ambient gas around the jet results in forming a thin gas layer between the jet and the liquid bath [Lorenceau et al, (2004); Eggers, (2001); Zhu et al, (2000)] in such a system. This ambient-gas entrainment realizes a non-coalescence jet in the bath. This is a key phenomenon to understand the dynamics of the impinging liquid jet. It has been known that the jet bounces off the bath surface against the gravity even after the penetrating to the liquid bath under a narrow range of condition on impinging jet velocity and flow rate of the bath. This unique behavior is often called as ‘the bouncing jet’ for Newtonian liquid[Thrasher et al. (2007)]. In the present study the authors focus on this ambient gas entrainment in the system that the impinging jet penetrates to coalesce into the flowing liquid bath; especially on the evaluation of the thickness of the entrained gas around the penetrated jet.
2. EXPERIMENT

Figure 1 shows the experimental apparatus. The apparatus consists of major three parts: jet generation system, flowing liquid bath, and observation system. Linear jet of 100-cSt silicone oil was produced from a nozzle attached to an overflow tank. This system enabled us to generate a jet of constant flow rate. The jet was impinged to the flow of the same fluid in a bath. Inner width, depth and height of the bath were of 320 mm, 20 mm and 50 mm, respectively. The flow rate in the bath was controlled by regulating valve. The flow was confirmed to have a linear profile at the test region. The jet generation system was placed above the bath at a designated height from the fluid surface in the bath. The impact velocity of the jet to the fluid in the bath was varied by varying the height of the jet generation system. The fluids of the jet and in the bath were recirculated by two pumps after the filter. The behavior of the impinged jet to the flowing fluid in the bath was observed with a high-speed camera of $1024 \times 1024$ pixel$^2$ at a frame rate up to 2000 fps. The jet and the fluid near the impinging jet was visualized under backlighting condition.

3. RESULTS AND DISCUSSION

3.1 Behavior classification of liquid jet in bouncing jet generation process

Four major behaviors of impinged jet were observed by changing the velocities of the jet and the flow in the bath. Typical examples of the major behaviors are shown in Fig. 2. In case of large difference between the jet velocity, $V_{\text{jet}}$, and the bath flow velocity, $V_{\text{bath}}$, the jet penetrates into the bath and bends towards the downstream direction in the bath as shown in Fig. 2-1. Entrained-air sheath wraps the impinged jet to realize that the jet never coalesces with the fluid in the bath until the air sheath breaks down. Tiny bubbles are formed and detach at the tip of the sheath. One can see an 'air pocket' does exist beneath the deformed free surface of the fluid in the bath to sustain the penetrating jet. If one decreases the difference $V_{\text{jet}} - V_{\text{bath}}$, the penetration length of the jet in the bath becomes shorter, and the air sheath breaks down right after the sustaining air pocket as shown in Fig. 2-2. In this case frequency of tiny bubble generation becomes higher. Noted here that the tiny bubbles detach at the bottom of the tip end. This is because the tip of the impinged jet is pinned by the boundary of the air pocket. In further decreasing the difference $V_{\text{jet}} - V_{\text{bath}}$, the bouncing jet [Thrasher et al.(2007)] is formed as shown in Fig. 2-3; that is, the impinged jet is bounced off the surface of the fluid flowing in the bath without any penetration into the bath fluid. The jet is sustained by the deformed free surface of the fluid in the bath with an air cushion between them. The bounced jet is bent due to the gravity.
and re-entry to penetrate into the bath. Further decreasing the difference $V_{\text{jet}} - V_{\text{bath}}$, the jet crawls on the free surface of the fluid in the bath after bouncing off as shown in Fig. 2-4.

The authors especially focus on the thickness of the entrained air sheath formed around the jet in the cases as shown in Figs. 2-1 and 2-2.

![Fig. 2 Typical examples of the behaviors of the impinging jet to the fluid flowing in the bath. (1): ($V_{\text{jet}}$, $V_{\text{bath}}$) [mm/s] = (1.36×10^3, 2.37×10^2), (2): (1.04×10^3, 2.37×10^2), (3): (8.31×10^2, 3.04×10^2) and (4): (5.44×10^2, 4.00×10^2)](image)

3.2 Measurement of thickness of air film

The authors try to evaluate the thickness of entrained air wrapping the penetrated jet. The thickness is evaluated at a position right beyond the air pocket sustaining the jet. As aforementioned tiny bubbles grow and detach from the tip of the jet coalescing to the bulk fluid. One can evaluate a mean gas flow rate around the jet by measuring a growth rate of the detaching bubble. Figure 3 indicates a successive snapshots of a growing bubble at the jet tip observed from the side. Assumptions are made for the bubble growth and for the air flow in the sheath around the jet; (i) the bubble at the jet tip grows in an axisymmetric manner, and (ii) the jet and the air sheath are co-axial cylinders, (iii) the velocity of the air in the sheath corresponds to the mean value of $(V_{\text{jet}}+V_{\text{bath}})/2$. The diameter of the periphery of the jet and the air sheath is evaluated from the recorded images of the jet in the bath from the side.

The images around the jet tip and around the bath surface where the jet is penetrating to the bath are detected with synchronized two high speed cameras. Field of view for each camera is of about 10 mm ×10 mm. Evaluated thickness of the air sheath around the impinged liquid jet in the case of the jet flow rate of 0.83 cm$^3$/s and the test fluid of 100-cSt silicone oil as functions of $V_{\text{jet}}$ and $V_{\text{bath}}$ is presented in Fig. 4.

![Fig. 3 Successive snapshots of a growing bubble at the jet tip observed from the side: $V_{\text{jet}} = 1.4×10^3$ mm/s and $V_{\text{bath}} = 2.4×10^2$ mm/s.](image)
Fig. 4  Evaluated thickness of the air sheath around the impinged liquid jet as functions of $V_{\text{jet}}$ and $V_{\text{bath}}$. Flow rate of the jet: 0.83 cm$^3$/s, test fluid: 100-cSt silicone oil.

Fig. 5  Evaluated thickness of the air sheath around the impinged liquid jet as a function of $V_{\text{jet}}$. Flow rate of the jet: 0.83 cm$^3$/s, test fluid: 100-cSt silicone oil, $V_{\text{bath}} = 2.4 \times 10^2$ mm/s.
4. CONCLUSIONS

Averaged air sheath thickness is about ten to several tens micrometer, which is rather less than the case of impinging jet to a pool [Lorenceau et al, (2004)]. The distribution of the thickness has a profile that exhibits a maximum in a range of the jet velocity under a constant V_{bath}. Figure 5 indicates the air sheath thickness against the jet velocity under the conditions of 0.83 cm³/s of jet flow rate and of 2.4x10² mm/s. The thickness increases as the jet velocity increases in the case of lower V_{jet}. The thickness abruptly decreases after the maximum point; this can be explained by considering shape of the free surface of the fluid in the bath sustaining the impinged jet. It can be explained by considering as follows; The momentum of the flowing fluid in the bath results in the jet bending toward the downstream direction, and this causes a pocket of the deformed free surface of the fluid in the bath. The entrained air around the jet snakes away toward the pocket because of the pressure gradient between the air sheath around the jet and the ambient pressure in the pocket, then the net amount of the entrained air around the jet penetrated into the bath fluid decreases.

Concluding Remarks

Entrainment of ambient gas around an impinging jet to a flowing fluid in the bath is examined. This ambient gas entrainment results in forming a thin gas layer between the jet and the liquid bath, which realizes a non-coalescence jet in the bath. The authors evaluate the thickness of the entrained gas around the penetrated jet as functions of the jet velocity and the velocity of the fluid flowing in the bath.

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