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Gas Flow Characteristics using Variation of Nozzle with Hydraulic Analogy Method

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Abstract: This research study about gas flow characteristics to a nozzle with assistance hydraulic analogies method. Characters gas flow vary depending upon character of static pressure, nozzle geometry and flow rate. Gas flow is very tough to identify because not seen directly by eye. So, it requires a special method to observe gas flow form. The proper way to examine it namely analogized gas medium with water. Research carried out by using the three forms nozzle, namely; convergent, convergent-divergent and parallel nozzles. Structures and shock-wave of jet observed using topography visualization method. The aim of research is appraise characteristics of jet, determine the profile of static pressure velocity and variations around locations of jet, understand existence the flow structure and shock-waves and predict the noise intensity from gas flow. Research shows that characteristics and structure of jet on the water flow is synonymous to gas flow. Flow rates and variation in profile of static pressure around jet at the critical ratio, Rh =1.5 is relative different to three nozzles that were tested. The jet structure is obviously different the critical ratio, Rh = 1.5 and ratio of Rh>1.6 were relatively equal. This study obtained that hydraulic analogy was able to give exact comprehension about the jet structure, obviously the shock-wave and understand of gas flow mechanisms. This study recommends that a new study on the characteristics nozzle and structures is hoped to give detailed information and description of flow characteristics and jet structures.

Key words: Hydraulic analogy, fluid, nozzle, jet, flow structure, mechanisms

INTRODUCTION

Nozzle is a tool that functions as a measuring tool to flow the liquids or gases. Characteristics of flow in jet have structures different flow for any changes in pressures and flow rates. The characteristics and gas fluid flow structure is quite complicated to be observed and understood. In another case, liquid fluid flow (water) is easier to be investigated and observed through of hydraulic analogies table installation assistance (Brocher and Makhsud, 1995, 1997). Phenomena and gas flow structure can be studied with a more specific way by analogying the gas and the water flow. Observing and understanding the structural gas flow characteristics and screech tone, mechanism is very complicated because the apparent flow structure was inconvenient to be observed. It is different from the liquid fluid flow (water) which can observed visually with unaided eye or through topography (Andre *et al*., 2013; Kumar *et al*., 2011) (Table 1).

This study trying to show results of experiment on the characteristics and structure jet from water flow that is analogous to gas flow to the three forms of tested nozzle geometries (Fig. 1). There are several studies to study gas flow characteristics but until now they not able to fore see or predict exactly how much noise power that was produced. In particular to gas fluid flow, jet cell structure and shock-wave in specified mach number, that is cause supersonic jet noise (aeroacustic) (Seiner and Manning, 1987; Panda, 1995) (Fig. 2). Andre *et al.* (2013) has said that the noise due to shock divided into two

Table 1: Summary of the hydraulic analogy principle

Two dimensional compressible gas flow	Water flow on the free surface (hydraulic)
Hydraulic gas γ = Cp/Cv = 2	Incompressible liquid fluid flow (water)
Temperature ratio (T/T_a)	Depth ratio of water (h/h_a)
Density ratio (ρ/ρ_a)	Depth ratio of water (h/h_a)
Pressure ratio (p/p_a)	Height ratio of water square $(h/h_a)^2$
Gas flow rate (V)	Water flow rate (v)
Propagation of sound speed (noise) $a = \sqrt{RT}$	Water wave propagation speed $c = \sqrt{gh}$
Mach number (Ma = v/a)	Froude number (Fr = v/c)
Shock-waves	Hydraulic jump

T_a, p_a, ρ_a, h_a: reference value (ambient conditions and ha: The height of water on the analogytable), Cp and Cv: Specific heat and g: Acceleration of sound gravity

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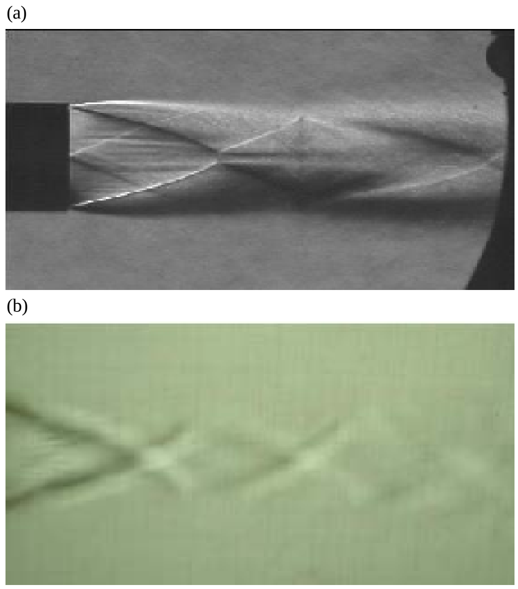

Fig. 1: Structure of supersonic jet shock-waves: a) Gas flow and 2) Water flow

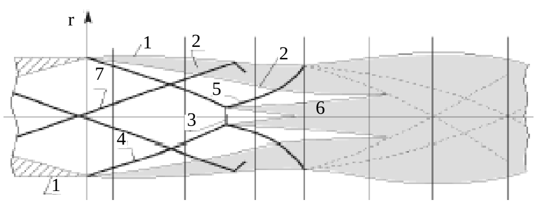

Fig. 2: Scheme of supersonic jet structure: 1. Nozzle, 2. Jet shear layer, 3. Mach disc, 4. Shock compression, 5. Shock reflection, 6. Shear layer behind the mach disc, 7. Nozzle shock 1, 2 outer and inner boundaries of the jet shear layer

different components, namely is screeching sound and a broadband. Therefore, it required depth and global understanding about structure and characteristics of flow, shock-waves and the apparent screech tone from gas flow mechanisms. In a research that screech tone intensity afford be altered substantially by the positioning of a comparatively small cylinder along the midline of jet flow by Buchanan *et al*. (2007). Through installation of hydraulic analogies table, it is expected to provide detailed information and an overview flow characteristics and structure jet, then phenomenon of jet gas flow can better understood.

MATERIALS AND METHODS

Theory: The study of fluids flow structure that flows in nozzle had been observed through a tool called hydraulic analogy several studies associated to fluid flow structures with this method to Brocher and Makhsud (1995) in a research test screech noise on the free surfaces hydraulic analogy using convergent nozzle. It was found that ratio of critical heights, convergent nozzle showed shock-cell structure. Then Brocher and Makhsud (1997) continue their research about mechanism of sound that is run with hydraulic analogy. This analogy was designed to utilize the distribution degree of water not interfere jet (Rani and Wooldridge, 2000). So that, intensity of tone is found relationship togradient of local static pressure at shock-second cell. It explains that the greater of sound intensity is relative to shock-cell.

Gradient of local static pressure is a function to ratio pressure jets (Brocher and Makhsud, 1997). So with hydraulic analogy can give better understanding than the mechanisms of screen tone. Experimental method can display directly form of jets noise in nozzle with low ratio pressures. So, this research is the right step to predict intensity of noise.

Description of the hydraulic analogies more advanced was described by Lavicka *et al.* (2007) and Buchanan *et al.* (2007). Kumar *et al.* (2009) also stated that the flow behind jet nozzle has become particularly attractive because impact on aerodynamics, structures and aircraft propulsion systems. Seen from momentum equations and physical quantities, analogous to two liquid type are summarized and displayed by Table 1. The characteristics and structures of fluid that flows through nozzle (jet) will different at each pressure change and flow rates (Brocher and Makhsud, 1995; Buchanan *et al*., 2007). The obvious difference in structure depends on geometry size of width and operation conditions (pressure and flow capacity) from nozzle. Fluid flow structure (jet) which comes through a nozzle depending on operating conditions of nozzle which are in this case divided into:

- When the fluid pressure in nozzle less than external pressure, then the jet condition is called "over-expanded" or the "imperfectly expanded"
- When the fluid pressure in nozzle equal to pressure outside the nozzle, jet in this condition is called "perfectly expanded" or "correctly expanded"
- When the fluid pressure inside of nozzle (at the exit) is more than the pressure outside of nozzle, then nozzle at this condition is called "under expanded" or "imperfectly expanded"

The operation of nozzle or jet for conditions "correctly expanded" is very seldom practical where the condition of jet structure cell is not visible (has not happened yet) and shock-wavess. In operation conditions nozzle where the jet "imperfectly expanded" (over-expanded orunder expanded), the apparent flow structure seems like the shock-cell and shock-wave (Makhsud, 1996). Gas flow structure is very influential on the apparent noise and the level of noise power intensity. As shown by research Zapryagaev (Fig. 1) and Makhsud (1996) (Fig. 1b) shows above the table and ha: water level on the analogy table outside of the nozzle. The structure of shock-wave forms supersonic jet from gas flow and water flow.

Figure 1a and b it shows clearly that the similarity in jet structure as a result of the visualization of water and gas flow (in this research). A profile jet structures displayed Fig. 2 from convergent-divergent nozzle to operating conditions nozzle is over expanded.

Eksperimental setup: Hydraulic analogy table installation was specifically designed for learning the flow characteristics and mechanisms of jet noise. A hydraulic analogy table installation is demonstrated in Fig 3, it consists of a water tank made of stainless steelandis equipped with a water filter which always maintained clean. To reduce vibration of the pump, so that foot of the analogy table is propped with vibration-damping (sand) and pipe installation using an elastic plastic pipe installed between pump and tank water of both channels. For the analogy table, it was made of glass (Length = 2 m, Width = 1.4 m, Thick = 0.015 m), it was also supported on every side so that, apparent deflection was as small as possible (<1/10 mm). To prevent wave reflection, the mounted corkon both sides from analogy table or wall and in the downstream (rear) was mounted regulator plate that is tilted <4°. The regulator plate was also works as a regulator degree of water on the analogy table.

Visualization techniques with the shadow method (shadowgraphy) or topography be used to observed structure characteristic from jet. The light source (fluorescent lamp) was placed approximately 80 cm top and bottom the table in which there was a mirror mounted 45°, so that, shadows visible in the mirror. The shadow that appears on the mirror can easily viewed through unaided eye and can be trapped by a camera video. Capacitor the nozzle flow velocity was measured with the measuring tool namely orificemeter or pitot meter to determines the velocity profile. Level (high) of water surface on the table was measured with needle mounted on micrometer. Fluctuations in water level can be specified with the assistance of optical sensors (fiber optics) MTI Model 1000 Fotonic Censor. The captured signals by optical censorsare transferred to the FFT analyser (HP 3582A) and from this tools, spectrum, coherence and phase angle wave were found. Fluctuations in water level measured on the FFT analyser tool was converted to value of noise intensity levels produced by water flow (nozzle). Three nozzles tested, namely: convergent nozzle, nozzle parallel and convergent-divergent (Fig. 4).

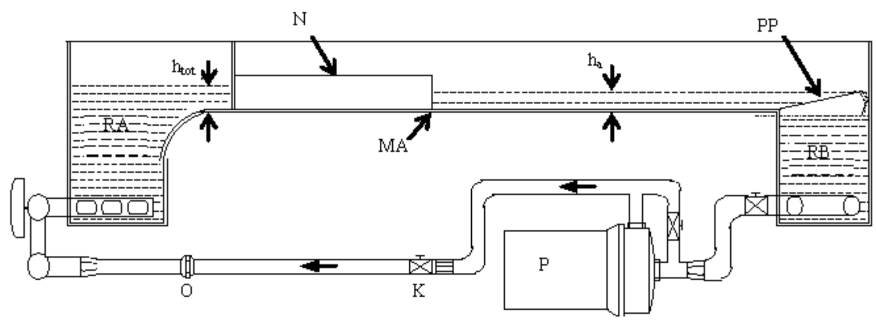

Fig. 3: Instalation of hydraulic analogy table research (side view). P: Pump, K: Valves, O: Orificemeter, RA: Upper reservoir, N: Nozzle, MA: Analogy table, PP: Water level control plate, RB: Lower reservoir, h_{tot}: Water level in the reservoir

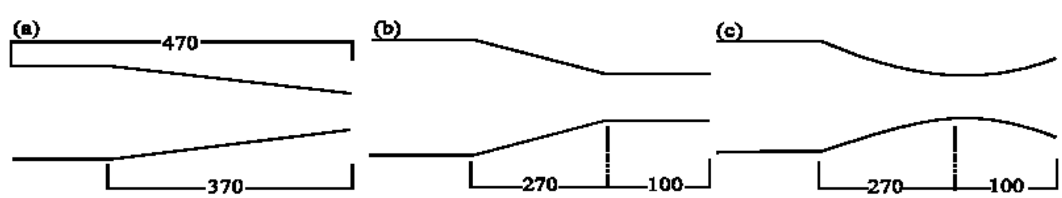

Fig. 4: Nozzle geometry form (measurement in mm). The width of the nozzle exit and throat W = 60 mm; a) Convergent nozzle; b) Parallel nozzle (blast tube) and c) Convergent-divergent nozzle

RESULTS AND DISCUSSION

Nozzle operating conditions at velocity profile of jet with critical ratio $Rh = h_{tot}/h_a = 1.5$ is demonstrated in Fig 5a for nozzle N_1 and Fig 5b for Nozzle N_2. Water level on the analogy table was ha = 27 mm with measurements position that was performed on 3 vertical points of Z (10, 15 and 20 mm) above the analogy table. Velocity profile was measured on transverse position of Y at nozzle exit section (X = 0), sources indicated relativity same level at each point of measurement for height measurements of Z are different. Level of measured velocity in equality was not morethan 5% and at point toward the nozzle wall, its velocity decreased. That's because effect of shear stress on the wall. In the measurement position of Y/W (between -0.2 and 0.2), transverse direction of the center nozzle showed same tendency from velocity values and position of Y/W about 0.4 velocity changes happened to be relatively higher because surface tension effects (W is the width of Fig. 11. Jet oscillation movement (nozzle N_3) nozzle). For both nozzles (N_1 and N_2) which were tested showed velocity profile and the same flow characteristics, while for the convergent-divergent nozzle (N_3) the velocity profile is not done because of flow structure was more complicated for Rh =1.5.

Water level measurement (head pressure) on the table was done with two objectives. First, to compare the level of water at the measurement point to circumstances beyond the nozzle (h_a), so, the flow was detected over pressure or under pressure conditions, it is because the principle of analogy $(h/h_a)2 = (p/p_a)$. Second, to determined the local surface in flux velocity, to specified the local Froude number Fr = V/vgh. Figure 6a Nozzle N_1 and in Fig 6b Nozzle N_2, that show distribution of water level (static pressure) along operation conditions jet nozzle with the ratio head $Rh = h_{tot}/h_a = 1.5$.

Fluctuations in ratio static pressure (h/h_a) throughout measurement position of the three jets to Y/W on the Nozzles N_1 and N_2 showed different relatively profile. The Nozzle N_2 generated static pressure profile along jet nozzle stend to be similar (X direction) and have not seen any visual shock-cell and shock-wave while the nozzle N_1 was visible (displayed) the shock-cells with long specific cell structure as mentioned in the nozzle (jet).

Jet structure that through a nozzle which it depends at the capacity of flow and geometry nozzle. This study was conducted to test multiple variations of discharge or flow capacity, ranging from critical head ratio with Rh = 1.5, Rh = 2.2. When the nozzle head was operated on head ratio with Rh>1.6 for nozzle N_1, then flow structure will be clear seen the shock-cell and shock-waves which is the main causeof aerodynamic noise. By obvious shock-cell or shock-wave in cell emission was interesting to be observed and studied deeply with the assistance of more accurate measuring tools. Length of nozzle structure and shock-cell that have been recorded by video camera

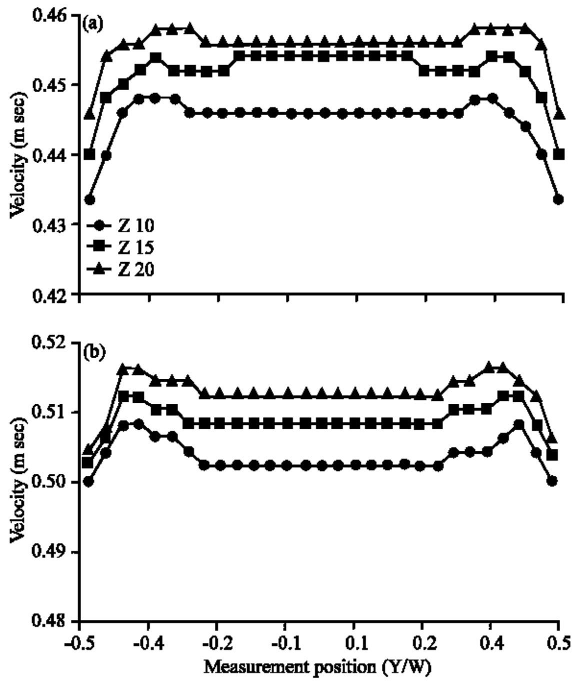

Fig. 5: Jet velocity profile at (X/W = 0 and Rh = 1.5)

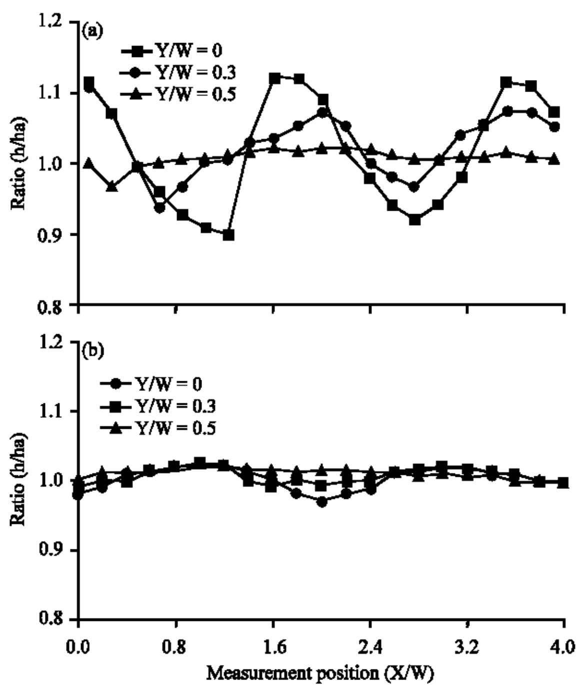

Fig. 6: Jet along the static pressure at Rh = 1.5

occurs because of method of the shadow as a source of support shown in the Fig. 7. Nozzle structure and shock-cell which were recorded from hydraulic analogy table installations showed the same phenomenon with nozzle from gas flow. In Fig .7a, clear that structure of jet flow showed the same structure and fluid flow characteristics of gas which was studied previously. This phenomenon reinforced our belief that the fluid flow of liquid (water) can be analogous to fluid flow of gas. During the three shapes nozzles geometry are tested under operation conditions in a particular nozzle which is shown that characteristics of jet and structure is relatively the same, except in the operating conditions from nozzle in ratio critical and ratio head Rh = 1.5 or ratio pressure Rp = 2.25 (Fig. 7).

When the nozzle works within critical ratio in the head ratio Rh = 1.5 or at a ratio pressure Rp = 2.25, then shock-cell structure and shock-waves at a jet seemed to be very clear to the Nozzle N_1 (Fig. 7a) while for Nozzle N_2 (Fig. 7b) shock-cells has not appeared yet and Nozzle N_3 Mach disc is visible (Fig. 7c). Shock-cells will show Nozzle N_2 when the flow capacity was enlarged from a height ratio approximately Rh≥1.6. Similarly what happened to Nozzle N_3 when the flow capacity is still low (critical ratio) which first emerged in jet is Mach disc and when increased water capacity with Rh≥1.65, then in jet looked shock-cell and shock-waves which is similar or identical to the nozzles N_1 and N_2 (Fig. 8).

At the installation under the analogy table have placed striped transparent paper that is useful to know or measure length of the shock-cellsoccurred in the nozzle. Operating conditions nozzle determined by flow capacity with Rh>1.9 generally jet nozzle has oscillated on the third tested nozzle. When the jet oscillated laterally as a result of the interaction flow and shock-waves, the shock-cell length varies periodically, so, value of length average of cells be caught. In the Fig. 9a for Nozzle N_1 it is clearly to see first and seconds shock-cell while the third cell seen to be relatively less clear, especially when the jet oscillated. Results of previous studies (Brocher and Makhsud, 1995), it was found that flow and shock-wave interactions at the seconds shock was source of the cell and causing jet noise in hydraulic analogy. The gas flow also been described by Tam (1995). Clear that the shock-waves in jet cause of aerodynamic noises. Tam (1995) also explained that for gas fluid flow have identified the cells and the shock-wave to the fourth shock-cell. Therefore in this research we can clearly see in shock-cells every second.

Figure 9b it shows that, the length of first shock-cell (L1) are relatively similar for all the three tested nozzles at flow conditions with the head ratio h_{tot}/h_a>1.65. Similarly length number on the first and seconds cell (L) for the

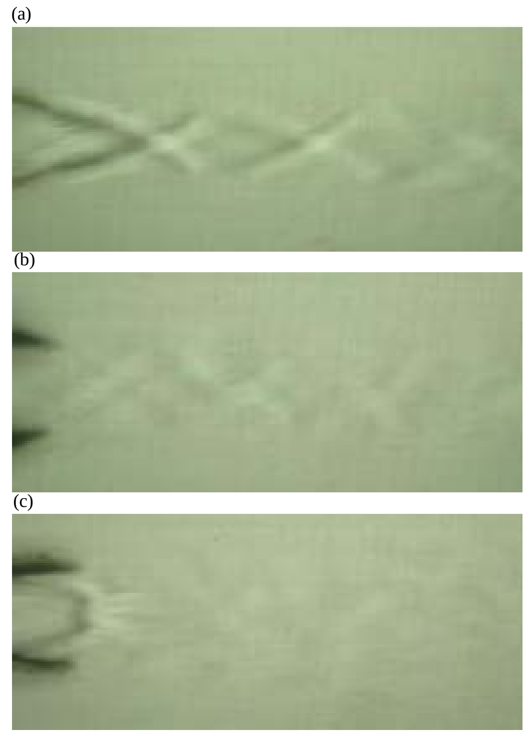

Fig. 7: Nozzle structure at head ratio Rh = 1, 5 (pressure ratio Rp = 2, 25); a) Nozzle N_1, b) Nozzle N_2 and c) Nozzle N_3

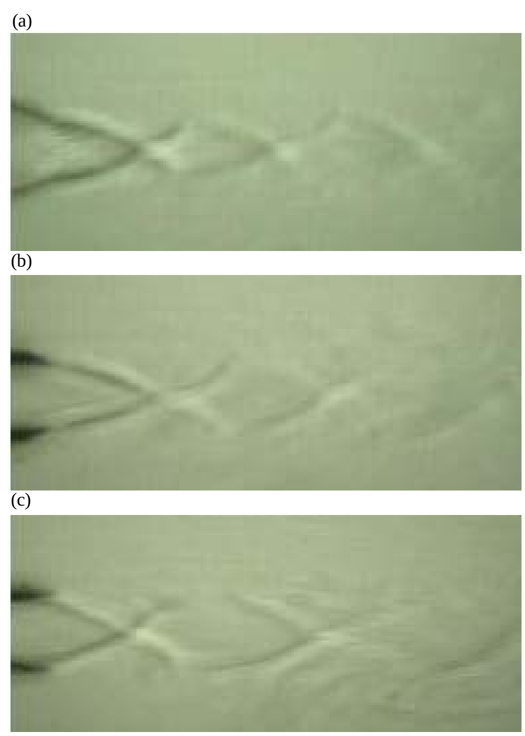

Fig. 8: Nozzle structure at Rh≥1.6; a) Nozzle N_1 (Rh = 1.6), b) Nozzle N_2 (Rh = 1.65) and Nozzle N_3 (Rh = 1.65)

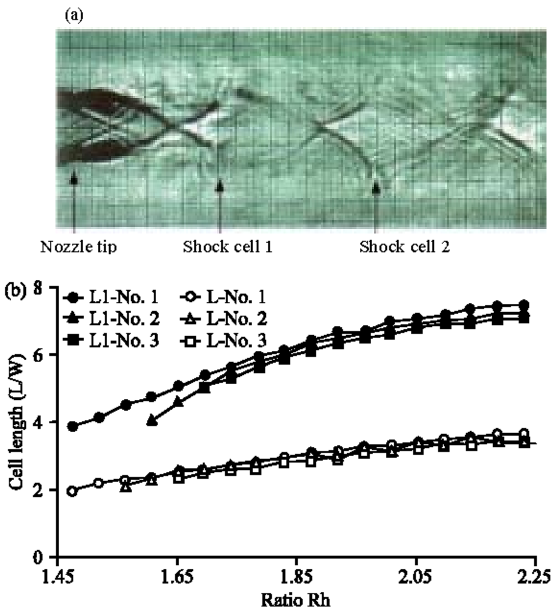

Fig. 9: a, b) Jet structure and the length of shock-cell as function of head ratio Rh

three nozzles is relatively similar in flow conditions $h_{tot}/h_a>1.8$. The length distinction of shock-cell for the three nozzles is relatively small and it will also affect noise generated intensity. The research results of Brocher and Makhsud (1997) and Makhsud (1996) shows length of the cell and shock-wave will affect the strength or the caused noise intensity. In flow conditions for ($Rh = h_{tot}/h_a$) is decrease shock-cell structure for the three tested nozzles are different, so, effect of noise power which is generated differently.

Results in analogies to the table showing the resources that mechanism of screech noise is a cycle of acoustic pure (acoustic wave) which propagated downstream to the boundary between jet sliding layer in the local velocity noise and wave propagated upstream into acoustic velocity on the outside or around the jet. Loop phenomenon that appears on the analogy table is purely acoustic different with previous the findings of researchers where the vortex is instability waves. These results indicate resources that length of circle is considered as the distance L (the noise source) is the distance between the nozzle tip and at cells shock in late secondly (Fig. 9a). Assuming that the noise around the jet velocity is equal to local velocity noise (atmosphere), then screech noise frequency is written as:

$$1/f = L\left[\left(\frac{1}{a}+V\right)+\left(\frac{1}{a}\right)\right] \quad \text{or}\; f = \frac{a(M+1)}{L(M+2)} \qquad (1)$$

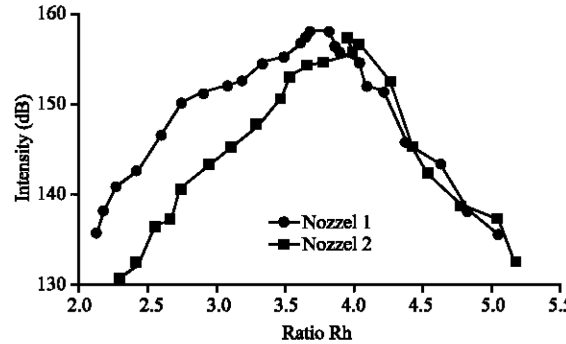

Fig. 10: Screech tone intensity as function of pressure ratio (Rp)

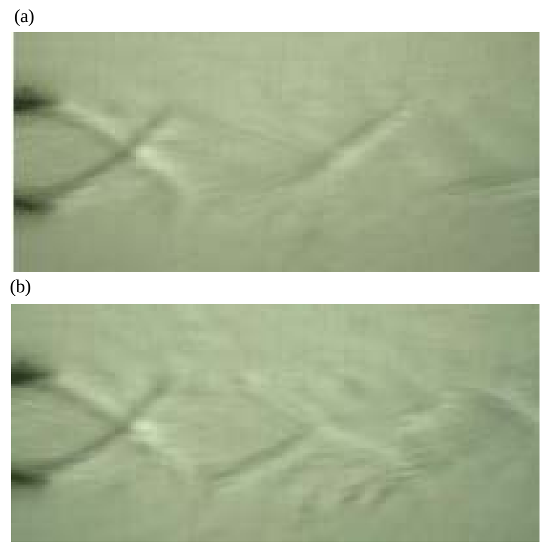

Fig. 11: Jet oscillation movement (Nozzle N_3): a) Oscillated to the right and b) Oscillated to the left

Where M is mach number average about boundary jet. Figure 10 showed that, noise intensity that was produced by the jet for Nozzles N_1 and N_2, showed the average of noise intensity for the Nozzle N_1 is higher than Nozzle N_2 (Makhsud, 1996). Acoustic intensity differences to the two nozzles morethan 10 decibels on test conditions with ratio pressure ($\tilde{p}/pa$) which is low at ($Rp<3.8$) and relatively equal to test conditions Ratio pressure, $Rp\geq 4$. This difference occurred because the produced flows structure (the length of shock-cell and shock-wavess) is different, although the capacity is equal flow.

Described gas flow instabilities by Seiner and Manning (1987) Also occur in jet tested of hydraulic analogy table installations. Figure 11 shows that, movement of jet unstable (oscillating to right and left) recordings through photos on the camera head ratio Rh = 1.85 or ratio pressure Rp = 3.4 for convergen-divergen

Nozzle N_3. Figure 11 clear that the jet oscillated to right (Fig. 11a) in certain and next under condition the jet oscillated to theleft (Fig. 11b). The jet showed a relatively stable movement on the condition head ratio, Rh<1.85 and oscillating movements of jet occurred when the flow capacity increased with the head ratio between Rh = 1.85-2.1. Further more when the increased flow capacity to achieve the head ratio Rh>2.1, then movement of jet will be best able. Conditions like this can be happenned because when the flow capacity increases, the flow velocity and energy movement will also increase, so that, energy can penetrate and lead back movement of jet to best able. Nozzle operation under the conditions where the screech noise is dominant, then the nozzle flow (jet) visually demonstrated the phenomenon of lateral oscillation motion. Obviously this phenomenon is seen with the eyes (without any tools) to test installation in hydraulic analogies table.

CONCLUSSION

Upon reviewing results of research and discussion concluded that: Hydraulic analogy installation can provide detailed information about characteristics and structure of jet flow, the apparent shock-waves and mechanism of screech noise. Jet structure in water flow resulted from used of hydraulic analogy table installations is visually similar to the results from jet flow gas.

Velocity jet profile is relatively same while static pressure around jet for the three tested nozzles showed the condition and different relative value especially for nozzle operating conditions for the critical ratio, Rh = h_{tot}/h_a = 1.5 or Ratio pressure Rp = 2.25.

The characteristics and structure of jet flow as seen in the three nozzles tested very different to nozzle operation conditions with critical ratio, Rh = 1.5 but for the nozzle operation conditions with ratio of Rh =1.6 (Nozzle N_1 and N_2) and the ratio Rh =1.65 (Nozzle N_3) has shows general structure of jet and shock-wavess are relatively similar.

Screech noise mechanism found on analogy table was pure loop of acoustic wave that propagate downstream in boundary layer around jet and the wave propagates upstream on the outside of the jet. Intensity values for resulted screech noise by the jet for Nozzle N_1 was higher average from the Nozzle N_2. Nozzle operation under conditions where the screech noise is dominant, so that, jet visually showed the phenomenon of lateral oscillation movement. Hydraulic analogy technique capable of providing detailed information about the structure of jet, the apparent shock-wave and to understand about gas flow mechanism of noise. Future research should be reduced screech noise characteristics of jet.

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