

SWIRLING STABILITY OF FLUID FLOW IN CYCLONE AT SUPERSONIC VELOCITY

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Abstract— Cyclone is device that use the angular momentum principle to separate the solid particle in the gas. There are many mechanism of working principle of cyclone in the industry. But not all of that mechanism is suitable for at that what we want. In this study, we are ready specific to focus on how the effect on the swirl stability when it flow at supersonic speed and also to study their flow behavior in the cyclone. By using mathematical modeling of k-epsilon RNG. In the standard k-epsilon model the eddy viscosity is determined from a single turbulence length scale, so the calculated turbulent diffusion is that which occurs only at the specified scale, whereas in reality all scales of motion will contribute to the turbulent diffusion. In this section, we used the numerical method k-epsilon RNG because it is more accurate to handle the high swirl flow. RNG is model to use for suitable condition with cyclone vortex. In this case of determine the stability of swirl then the use of RNG model is very better than Realizable. RNG k- ϵ model is design to handle the swirl flow compare to the Realizable k- ϵ model (Hreiz, 2011). The swirl number will shows the stability of swirling flow at velocity Mach 1 and velocity Mach 4. The vortex core region at velocity Mach 1 is very smooth when we compare to the velocity at Mach 4. In this study, we can summarized that the stability of swirling flow is can come in various form and at the same time when it is bounded with vortex. Streaky speaking, the stability of swirl in cyclone at supersonic speed is not stable. But in this experiment the slowed the velocity the stable it is. At the same time, the study of behavioral of supersonic flow in cyclone is a something news because of the vortex breakdown was found. Not much literature today was study about the supersonic flow in cyclone.

I. INTRODUCTION

The separation process between solid and gas usually use the cyclone device. This device is provide high efficiency of separation when we compare to the others device. Cyclone is device that use the angular momentum principle to separate the solid particle in the gas. There are many mechanism of working principle of cyclone in the industry. But not all of that mechanism is suitable for at that what we want. In this study, we are ready specific to focus on how the effect on the swirl stability when it flow at supersonic speed and also to study their flow behavior in the cyclone.

There are many section that study the stability of swirl or also

we know that vortex such as the areas in meteorology, astronomy, aeronautical engineering and others. The great ideal and several of method that study the supersonic behavior at today. In study of cyclone separation, they reported that the efficiency of separation process is depend on how much the particle can be remove. From this statement, so many literature talk about how to optimize the cyclone separator one of them is by using supersonic flow. The

supersonic flow is the most important part that we need to consider first. Supersonic flow is also tend to disturb the swirling of flow because of high turbulent flow tend to affect the stability of flow stream. So many research was found that the supersonic flow play the important role for increase the efficiency of burning process also.

In this study, we use the computational fluid dynamic discipline to understand the behavior of supersonic flow. The experiment is conducted by using Navier-Stoke equation and plus the numerical method by using mathematical modeling of k-epsilon RNG (Sambasivam, 2014). In the standard k-epsilon model the eddy viscosity is determined from a single turbulence length scale, so the calculated turbulent diffusion is that which occurs only at the specified scale, whereas in reality all scales of motion will contribute to the turbulent diffusion. The RNG approach, which is a mathematical technique that can be used to derive a turbulence model similar to the k-epsilon, results in a modified form of the epsilon equation which attempts to account for the different scales of motion through changes to the production term.

A. Theory of Stability of Swirling Flow

Stability of flow in cyclone is so important in the design of cyclone efficiency. In common knowledge, cyclone will swirl in according to the angular momentum inside the cyclone and at the same time the particle in the gas is separate by the angular momentum. The tangential velocity that acting on the particle and gas inside the cyclone will lead it to separate between each other. At the same time, the swirl is happen and produce a vortex. This swirling we need to control to make it balance to make sure the efficiency of separation is at optimum condition.

The factor that effect the stability is because of uncontrollable of swirling flow inside it. This will lead the separation process between particle and gas is not balance. According to the Jingsheng, (2005), the stability of swirl is due to the high swirl number. The swirl number is a dimensionless where it define as,

$$\text{Swirl number, } S = \frac{\text{circumferential velocity, } w}{\text{axial velocity, } V_a} \quad (1)$$

Where the symbol of w is circumferential velocity and v_c is axial velocity. According to Huang (2005), he said that when the swirl number is increase then it will make increase the stability amplitude.

B. Supersonic Flow Behavior in Cyclone Separator

When we talk about the cyclone device, we imagine that how it work. Cyclone separator is use commonly in industry to various principle and application. So many cyclone was found today that have the difference design but the working principle is still the same because cyclone is the device that use the angular momentum to separate the two material such as dust particle in air. In this manner, we study the behavior of air flow inside the cyclone separator at supersonic speed. Usually, in other literature, we only

found that their study at low and high velocity only. Not much literature that study about the efficiency of the cyclone separator at supersonic velocity. The supersonic flow is very complicate to understand because it is involve high turbulent flow and also contain the supersonic characteristic such as wave propagation and shock wave.

In this case also, we not impressed with compressible flow because we usually found the study of gas flow behavior in the literature. The study of compressible flow always deal with the ideal gas assumption. But in this study, we assume that the flow of gas is non-ideal gases. Moreover, the swirling of vortex flow in the cyclone is also taking an action because it is play an important role. The efficient of cyclone will abrupt due to instability of swirling vortex. In this case the hypothesis is focus on the swirling vortex characteristic at supersonic speed because no other literature is found that study the vortex characteristic. Besides, the

II. METHODOLOGY

A. Mathematical Model

The swirling fluid flow can be describe by Navier-Stoke equation. In this case, the swirl flow behavior in the cyclone is due to change in their magnitude and momentum. This equation is explain the behavioral of fluid dynamic and we also can predict the behavioral of flow. The Navier-Stoke is explain about the momentum of fluid dynamic where it is application from the second law of motion. From this equation we can determine the flow behavior of fluid dynamic in cyclone. According to Navier-Stoke equation below,

$$\begin{aligned} \frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u^2)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} + \frac{\partial(\rho uw)}{\partial z} &= -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x} \left(\lambda \nabla \cdot \mathbf{V} + 2\mu \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left[\mu \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right) \right] + \frac{\partial}{\partial z} \left[\mu \left(\frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} \right) \right] + \rho f_x \\ \frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho uv)}{\partial x} + \frac{\partial(\rho v^2)}{\partial y} + \frac{\partial(\rho vw)}{\partial z} &= -\frac{\partial p}{\partial y} + \frac{\partial}{\partial y} \left[\mu \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \right) \right] + \frac{\partial}{\partial y} \left(\lambda \nabla \cdot \mathbf{V} + 2\mu \frac{\partial v}{\partial y} \right) + \frac{\partial}{\partial z} \left[\mu \left(\frac{\partial w}{\partial y} + \frac{\partial v}{\partial z} \right) \right] + \rho f_y \\ \frac{\partial(\rho w)}{\partial t} + \frac{\partial(\rho uw)}{\partial x} + \frac{\partial(\rho vw)}{\partial y} + \frac{\partial(\rho w^2)}{\partial z} &= -\frac{\partial p}{\partial z} + \frac{\partial}{\partial z} \left[\mu \left(\frac{\partial w}{\partial x} + \frac{\partial u}{\partial z} \right) \right] + \frac{\partial}{\partial y} \left[\mu \left(\frac{\partial w}{\partial y} + \frac{\partial v}{\partial z} \right) \right] + \frac{\partial}{\partial z} \left(\lambda \nabla \cdot \mathbf{V} + 2\mu \frac{\partial w}{\partial z} \right) + \rho f_z \end{aligned} \quad (2)$$

Where ρ and t is density and time respectively. P and Re is pressure and reynold number respectively. Also, τ is the shear stress between fluid and wall. This study use the navier stoke equation that involve in the ANSYS software to analyze the fluid flow in the cyclone.

B. Numerical Method

In this study, we use the ANSYS software FLUENT done this experimental. By using the simulation we can predict result before we start with reality. In this experimental, the numerical method is apply. This mathematical modelling is already contain in that software where it is Navier-Stoke equation.

In this section, we used the numerical method k-epsilon RNG because it is more accurate to handle the high swirl flow. RNG is model to use for suitable condition with cyclone vortex. In this case of determine the stability of swirl then the use of RNG model is very better than Realizable. RNG k- ϵ model is design to handle the swirl flow compare to the Realizable k- ϵ model (Hreiz, 2011).

C. Geometry and Physical Model

The geometry is consider it is real cyclone where it is design to handle supersonic velocity. The dimension below is shows for the cyclone separator that use the material type is aluminum and the thickness is 0.05 m. At the inlet the use of rectangle duct is very suitable when compare to the cylindrical shape when to see the swirl effect.

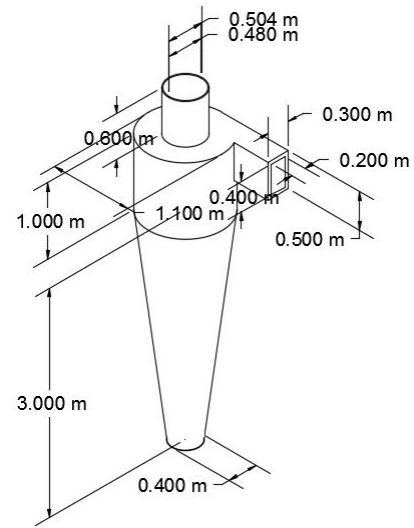


Figure 1: The dimension of cyclone separator for supersonic speed flow.

The type of fluid is air only because we want to study the flow behavior only not the efficiency of separation process. The model of viscous is using the k-epsilon model with RNG that combine with swirl dominate and swirl factor is 0.7. Besides, the velocity is at supersonic velocity where we running the simulation using the two difference velocity. The velocity of air enter the cyclone at 343 m/s and 1372 m/s where it is usually define as velocity at Mach 1 and Mach 4 respectively.

D. Solution Method

By using the ANSYS FLUENT simulation the analysis can be done using many of iteration number. This simulation experiment was running at transient process where the time step is 0.001 s and number of iteration is 2000. The solution method in this simulation is using standard initialized that compute at inlet. The result for each time step is saving in the CFD-post and all component variable is selected to make the animation. The animation of vortex breakdown for velocity at Mach 1 and Mach 4 is shows at the Table 3 and Table 4.

III. RESULTS AND DISCUSSION

A. The Stability of Swirling Flow in Cyclone

In this study, the stability of supersonic flow in cyclone is not stable because of swirl behavior. This because the stability is found by tracing their vortex. According to the vortex steam, it seeing not stable because of the instability of vortex swirl. In this case, we can consider this two Mach number is not stable but we can see between this two the most stable is depend on their swirl number and vorticity. Swirl number is tell about how the swirling shape is found by tracing the radial and axial flow. According to Harvey (1962), the experimental result was proof that the vortex breakdown is not due to instability and it is supported by Hall's Research (1972). So in this study we cannot directly said that the swirl at supersonic flow in the cyclone is not stable. The difference of swirl number is show that the higher swirl number the high tendency to disturb amplitude instability.

Vorticity

To determine the stability of swirl the vorticity is also bounded for this study because it tell us the tendency of a fluid particle to rotate or circulate at a particular point. It is mathematically defined as the curl of velocity. As we can see from the figure below, it shows that the difference between the two vorticity for Mach 1 and

Mach 4. Vorticity is apply the Gauss' Divergence Theorem where it define as,

$$\int_{V_0} \text{div } \omega \, dv_0 = \int_S \omega \cdot n \, dS \quad (3)$$

Where the symbol S and v is surface area and volume flowrate respectively. V_0 is volume and ω is vorticity field is such that its divergence is always zero as define below,

$$\text{div } \omega = \text{div}(\text{curl } u) = 0 \quad (4)$$

This means that the lower the vorticity number of the flow than the swirl flow become more stable because of vorticity is approach the zero it become more stable in their circulation flow field (Warsi, 1993).

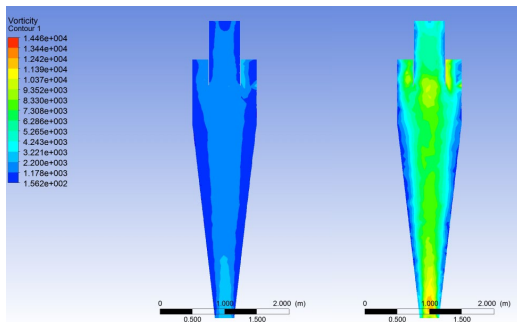


Figure 2: The figure is show for vorticity contour region between Mach 1 (left) and Mach 4 (right) where it compute at the middle plane by facing to the suction air.

The velocity at Mach 1 has the lowest number of vorticity when we compare with velocity at Mach 4. Because the swirl and vorticity is have the same meaning, than the swirl flow at velocity Mach 1 is more stable than the velocity at Mach 4. This also show that the circulation field is more stable at the velocity Mach 1 than the velocity at Mach 4.

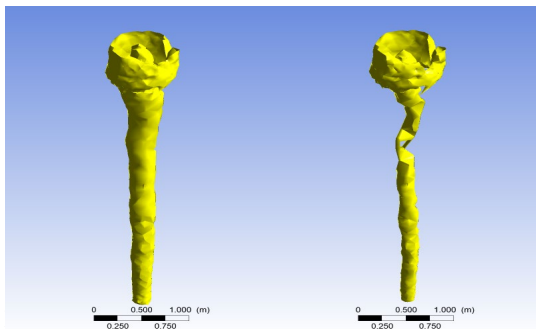


Figure 3: The figure is show for vortex core region between Mach 1(left) and Mach 4 (right) where it compute at level 0.45.

Swirl Number

The swirl number will shows the stability of swirling flow at velocity Mach 1 and velocity Mach 4. Consider to the Figure 3, from the naked eye we can see that the comparison of the vortex core where it indicate that the stability of swirl vortex. The vortex core region at velocity Mach 1 is very smooth when we compare to the velocity at Mach 4. The vortex core at the velocity Mach 4 is very rough and contain the imbalance on the swirling of vortex. Moreover, the vortex at velocity Mach 1 is very width than Mach 4. In this case we no need to consider the swirl number because by using the vorticity and the observation from the vortex core region it is enough to indicate the instability of swirling flow in the cyclone at supersonic speed.

The Figure 4 shows for the velocity that acting along the vortex

core region at velocity Mach 1. The velocity along the vortex core is compute from the Y-axis from -3 at the bottom outlet and until the top outlet. From the graph, we can see that the graph line pattern at the top is the same with the graph at Figure 5 Mach 4.

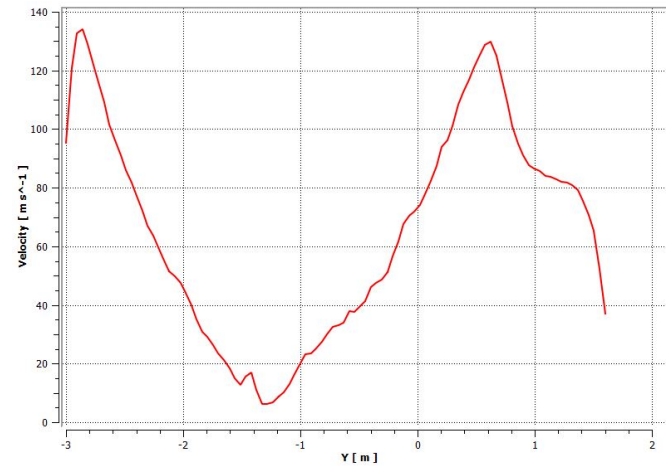


Figure 4: The figure shows the graph of velocity that varies along the vortex core region at the center of cyclone separator at velocity Mach 1.

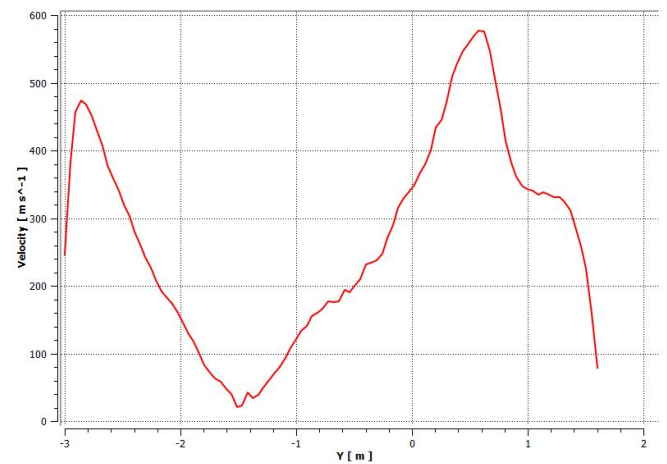


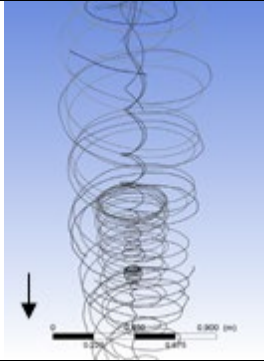
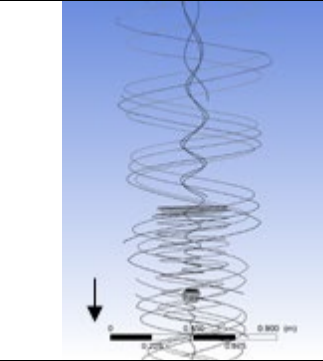
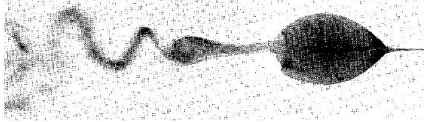
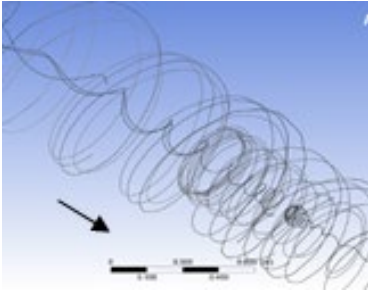
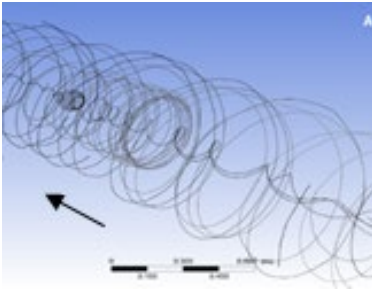
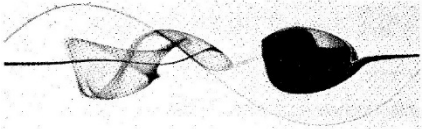
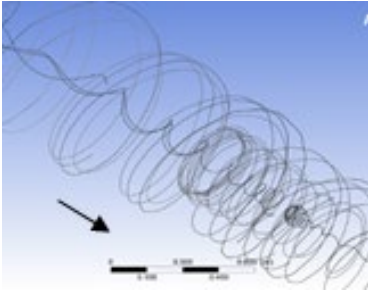
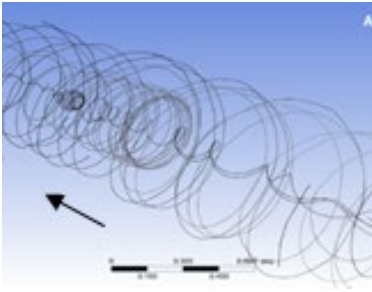
Figure 5: The figure shows the graph of velocity that varies along the vortex core region at the center of cyclone separator at velocity Mach 4.

But in this case it velocity is difference when the graph is moving down from the coordinate 1.6 Y-axis until the -1 Y-axis. From this point the graph pattern is starch to changes. This indicator shows that the velocity is become change their behavior at the vortex core where it is consist of difference transition of vortex breakdown. The velocity at vortex core at Mach 4 is slowest than vortex velocity at Mach 1. This is phenomena due to the vortex breakdown effect that discus at the next section.

form where we cannot predict it. There is some type of vortex breakdown have been discover today where it is contain forth type which is Axisymmetric, Bubble, Spiral and Double Helix vortex breakdown.

In our experiment, it shows that at the Mach 1 the vortex breakdown was seen like Bubble and Spiral Vortex Breakdown and followed by Double Helix Vortex Breakdown. This vortex breakdown that are exist in this simulation is the same like discover by Sarpkaya's real experimental. Table 1 is shows the comparison

Table 1: The analysis result from the simulation and experimental that include the bubble, spiral and double helix vortex breakdown in the cyclone separator at velocity Mach 1.

MACH 1 <i>Bubble, Spiral and Double-Helical Vortex Breakdown</i>		
Simulation Result		Experimental Result
		 The formation of axisymmetric breakdown include with small bubble and spiralling motion.
		 Single bubble formation followed by the formation of helix vortex breakdown.
		 The spiral vortex breakdown form after several rotation of helix vortex breakdown formation.
		Note : Gravity (Sign) ↓

B. The Behavioral of Supersonic Flow

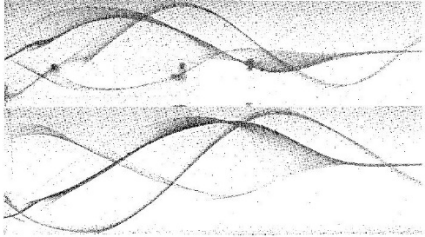
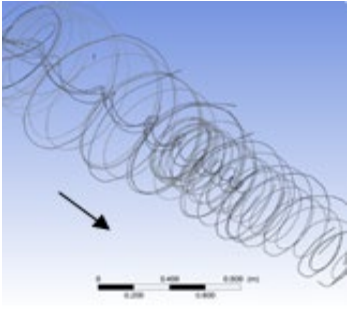
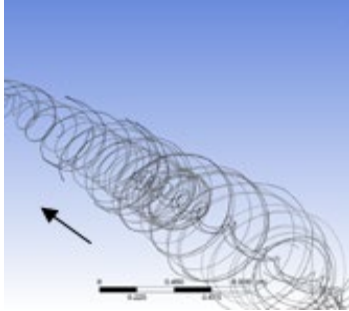
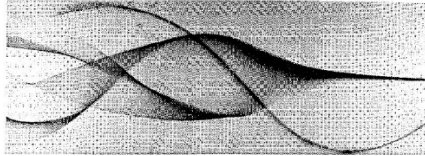
Vortex Breakdown

In this objective the finding is found a something new that happen in cyclone where the shape of stream at the vortex. Usually we found in literature the vortex in cyclone is always stable. But in this case it found the new one because by using mathematical model RNG the vortex breakdown was found where it is different for difference Mach number. Today, the vortex breakdown is still in debate for section in their theoretically and how it happen (Smith, 2000). Research by research is already done but still not have the confirm answer. According to the Benjamin (1992), vortex breakdown is happen due to the phenomenon analogous to hydraulic jump in open-channel flow. He considered the breakdown as a transition from a uniform state of swirling flow to one where stationary waves of finite amplitude were present.

In various research study shows that the behavior of the vortex breakdown that there have been discover today. The result from the simulation show that the vortex breakdown where it is difference between two Mach number. At Mach 1, the vortex breakdown formation is like single bubble that is approximately same with the experimental result that was done by Sarpkaya. According to Sarpkaya (1971), the type of vortex breakdown can change their

between our simulation result and Sarpkaya's experimental result. The transition type of bubble and spiral vortex breakdown is usually to occur and it is place closed each other and the bubble formation is maintain at that location that it start exist (Sarpkaya, 1993). The difference here is Sarpkaya was claimed that the bubble transition is occur at quite some time. But in this experiment, the bubble transition is continue to occur until at the end of the operation. In this case also, the formation of the transition of vortex breakdown at velocity Mach 1 is shows at the Table 3. The formation of transition is start with the double-helix and followed by the bubble vortex breakdown. The vortex breakdown is continue with the spiral transition.

Table 2: The analysis result from the simulation and experimental that include the double helix vortex breakdown in the cyclone separator at velocity Mach 4.

MACH 4 Double-Helix Vortex Breakdown		
Simulation Result		Experimental Result
		
		The double-helix vortex breakdown formation at the top and front view and the off-center filament.
		
		The clear image of double-helix vortex breakdown that reorted by Sarpkaya's experiment where it occur at Re=1700 and Circulation number at 2.35.
		Note : Gravity (Sign) ↓

At Mach 4 velocity, the double helix formation is happen inside the cyclone. The behavior of this transition type is already compare with the experimental result at Table 2. From the Sarpkaya's observation, he said the double helix is quite sensitive to upstream and the same goes with downstream disturbances. Moreover the emitting of vibration or slightest fluctuation in flow by the external system forced it gradually to deform (Althaus, 1993). Also, it is take indescribably complex forms or to rotate relative to the tube and gradually break down in the form of many secondary spirals. In our experiment it is look the same with what Sarpkaya said.

To see it for more detail, we can consider to the Table 4 where it show the step of the formation of double-helix vortex breakdown. The transition of Double-Helix vortex breakdown is very sensitive to the small disturbances because it is taking place by degrees of expands and breaks up into turbulences until it not detectable to swirl. Sarpkaya also reported that this type of transition is not produce a bubble because it happen at relatively low Reynold number and high circulation number.

IV. CONCLUSION

In this study, we can summarized that the stability of swirling flow is can come in various form and at the same time when it is bounded with vortex. Streaky speaking, the stability of swirl in cyclone at supersonic speed is not stable. But in this experiment the slowed the velocity the stable it is. At the same time, the study of behavioral of supersonic flow in cyclone is a something news because of the vortex breakdown was found. Not much literature today was study about the supersonic flow in cyclone. Moreover, the vortex breakdown is still under intense debate among scientists and mathematicians. It has not yet proved clearly how it happened. The formation of vortex breakdown is enough to support the evidence of the swirl stability at supersonic speed (Ruith, 2003).

Besides, this study show that to design the cyclone separator

that can be operate at supersonic speed is not easy because of so many factor that we need to consider such as the swirl stability. It proof that the very high velocity flow in cyclone it will disturb the stability amplitude because of swirl of the vortex (Gallaire, 2006). This is clear that the operation of cyclone separator at supersonic flow will tend to abrupt the particle in the cyclone because of the instability vortex swirling.

Furthermore, the study of supersonic flow behavior in the cyclone is not quite enough (Yang, 2017). This is because it is not much we know about supersonic because it is play with the high mathematical technique. Therefore in this future study we will analyze the behavior of supersonic shock wave in the cyclone. The supersonic flow is very important for the part of separation that need of supersonic behavior whether in industry of manufacturing or the use of everyday human life.

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APPENDIX

Table 3: The formation of vortex breakdown transition time step in second for the velocity Mach 1.

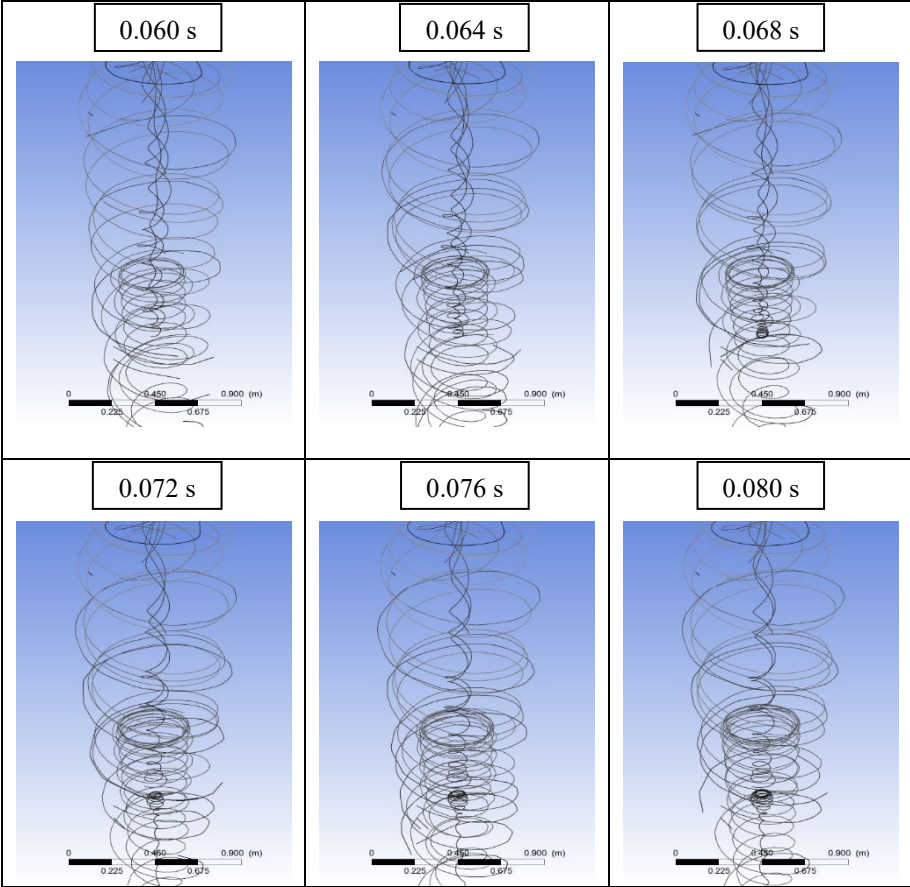


Table 4: The formation of vortex breakdown transition time step in second for the velocity Mach 4.

