Optimizing Different Angles of Venturi in Biodiesel Production Using CFD Analysis

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ABSTRACT: *The purpose of this paper is to find the optimal geometry of Venturi for the production of biodiesel by hydrodynamic cavitation. Intensive methods such as hydrodynamic cavitation eliminatethe limitation of mass transfer in the transesterification reaction.In this paper, a venturi design was developed to create cavitation in biodiesel production.The most important property of venturi in creating cavitation and retrieving the pressure is the convergence and divergence angles.The four convergence angles of 22°, 20°, 17° and 15° and four divergence angles of 12°, 10°, 7° and 5° in Gambit 2.4 software were designed and evaluated with Fluent 6.3 software and their CFD was analyzed.The maximum pressure recovery (85% of input pressure) and cavitation generation was for venturi 17-10 (Convergence angle 17° and divergence angle 10°), which was used in the setupexperimental of biodiesel production.The biodiesel production efficiency with this venturi was 95.6%.The FTIR spectrum of the biodiesel was taken to confirm its purity.*

KEYWORDS: *Biodiesel; Venturi; Fluent; CFD; Hydrodynamic cavitation.*

INTRODUCTION

Increasingenergy demands, depleting fossil fuel reserves andenvironmental issues call for a promising alternative green fuel. One possible solution is the introduction of biodiesel as analternative fuel [1]. Biodiesel can be produced by various methods [2–5]. Mixing/heating is the most commonprocess worldwideindustrial application for biodiesel production. This productionprocess consume a lot of energy, high catalyst, high molar ratio(alcohol to oil) and longer time due to mass and heat transferlimitation (immiscible of alcohol and oil) to produce biodiesel.Considering these limitations, there is strong quest to develop anefficient, time saving, economically functional and environmentallyfriendly biodiesel production intensification process at industrialscale.

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Keeping this aspect into consideration, several intensificationprocesses have been developed, such as hydrodynamic cavitation, ultrasound and micro wave [6-10]. Among recently developed techniques, hydrodynamic cavitation is a potential method for biodiesel production at industrial scale due to its easy scale-up property. Hydrodynamic cavitation has the other advantages such as:biodiesel conversion, reactionrate, time, chemical consumption, energy consumption, environmental friendly and safe [11, 12].

Cavitation is generated by the flow of liquid under controlled conditions through simple geometries such as venturiand orifice plates[13].The pressure recovery is much better for the venturithan the orifice plate, but there is no complete pressure recovery[14].Venturi consists of a converging section, throat and a diverging section as shown in (Fig. 1), D1: entrance diameter, d: throat diameter, D2: exit diameter).A venturi can also be used to mix a fluid with the other fluids[15].The behavior of the fluid as it passes through the venturi is understood by writing the Bernoulli equation using the conditions at the entrance, the throat, and the exit. Bernoulli's principle can be derived from the principle of conservation of energy[14, 16].

The objective of this research work was to find out optimum geometry of venturi for biodiesel production by CFD analysis. In this case, venturi was used as mixingequipment by creating cavitation.The goal of Venturi's hydrodynamic analysis was to carry out a transesterification reaction with a yield of more than 90%.Different combination of four convergence angles of 22°, 20°, 17° and 15° and four divergence angles of 12°, 10°, 7° and 5° in Gambit v2.4 software were designed and analyzedwith Fluent v6.3. Pressure contour and velocity contour were evaluated in Fluent software. The maximum pressure recovery and cavitation generationwas for venturi 17-10 (Convergence angle 17° and divergence angle 10°), which was used in the setup laboratory of biodieselproduction.

THEORITICAL SECTION

Hydrodynamic analysis in a venturi

Energy is conserved in a closed system, that is, the sum of potentialand kinetic energy at one location must equal the sum of thepotential and kinetic energy at any another location in the system.If potential energy decreases at one location, the kinetic energymust proportionally

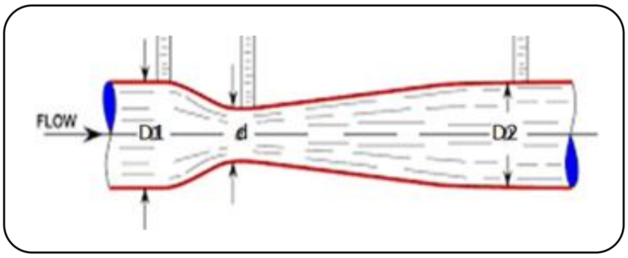

Fig. 1: Venturigeometry.

increase at that location.According to Fig. 1, the fluid now entersthe throat of the venturi with a new diameterd, which is smaller than D1. In a closed system, mass can be neither created nor destroyed (law of conservation of mass), and as such, the volumetric flow rate at D1 must equalthe volumetric flow rate at d. If the area at location d issmaller than D1, the fluid must travel faster to maintain the samevolumetric flow rate. This increase in velocity results in a decreasein pressure which follows Bernoulli's equation[17,18]. In this process, remarkable energy isreleased locally which increases the local pressure and temperature. Such increments in pressure and temperature favor the forwardreaction [19]. The reaction speeded up due to increasing number of energetic collisions within the cavities, which is similar to the supercritical condition [20]. Besides the continuity equation (i.e., Mass Conservation Equation) andNavier-Stokes Equation (i.e., Momentum Conservation Equation),turbulent flow equation was also needed as one of the basic controlequations. In the Descartes Coordinate system, the forms of the basic controlequations were list as follows [21]:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{1}$$

Navier-Stokes Equation:

$$\frac{\partial(\rho u)}{\partial t}+\nabla\cdot(\rho u u)=-\frac{\partial p}{\partial x}+\mu\nabla^2 u+F_x \tag{2}$$

$$\frac{\partial(\rho v)}{\partial t}+\nabla\cdot(\rho v u)=-\frac{\partial p}{\partial y}+\mu\nabla^2 v+F_y$$

$$\frac{\partial(\rho w)}{\partial t}+\nabla\cdot(\rho w u)=-\frac{\partial p}{\partial z}+\mu\nabla^2 w+F_z$$

Where, *t*is time；*u* is flow rate vector，and *u*, *v*, *w*are the tree sub values of ***u*** in directions of *x*, *y*, *z*；*ρ* and *μ* are the water density and dynamicalviscosity coefficient,

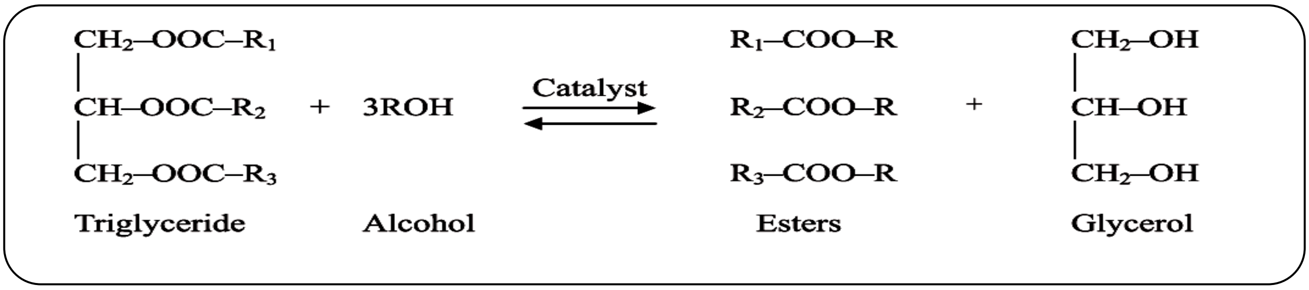

Fig. 2: Transesterification reaction of triglycerides and alcohol.

respectively ; *P*is the water pressure on the micro flowunit ; *Fx*, *Fy*, *Fz*are the mass forces of the micro flow unit in the directions of*x*, *y*, *z*. If the mass force was just gravity, and the direction of *z* was vertical upward, in this case, we can get that *Fx*= 0, *Fy*= 0, *Fz*=− *ρg*.

The purpose of this paper is to achieve optimal geometry of Venturi for the creation of hydrodynamic cavitation and removal of the transfer of mass between alcohol and oil in the transesterification reaction. Pressure recovery in this venturi was achieved at 85% efficiency. In addition, biodiesel yields were obtained by hydrodynamic cavitation at 95.6%.

Geometrical modelling and mesh generation

Methodology

In this research, the transesterification reaction was used to produce biodiesel. Trans-esterification reaction is the reaction between triglyceride (oil) and alcohol in the presence of a catalyst (Fig. 2). The product of this reaction is glycerol and biodiesel (ethyl ester). Waste Cooking Oil (as an oil source), methanol (alcohol) and potassium (catalyst) was used for transesterification reaction.

For CFD simulation, the geometry of the venturi, meshing of venturi, and the boundary of the system were defined by Gambit software (version 2.4).Finally a mesh file is imported to Fluent software (version 6.3) for hydrodynamic analysis. In Fluent desired density based solver was selected and then boundary conditions were determined. After entering the required information, Fluent is now ready to simulate the biodiesel flow in Venturi.

Geometric Modelling and Meshing of Venturi

In this paper, the effect of convergence angle and divergence angle of venturi on pressure recovery and generation of cavitation was investigated. Fig. 3 shows venturi geometry. After making geometry, next step is to mesh the geometry. Mesh sizes were kept different for zones. In Gambit, for meshing quad element with map type was selected. Fig. 3 shows venturi mesh with quad type meshing.

CFD Analysis

In this research, Fluent software (version 6.3) was used for hydrodynamic analysis. Main focus was on pressure recovery and generation of cavitation for different types of venturi. In CFD analysis selection of k-epsilon model. In standard *k-ε* turbulent flow model, the expression of turbulent flow kinetic energy *k* and dissipation ratio*ε* was listed as follows [21]:

$$k=\frac{1}{2}\left(u'^2+v'^2+w'^2\right) \tag{3}$$

$$\varepsilon=\frac{\mu}{\rho}\left(\frac{\partial u_i'}{\partial x_k}\right)\left(\frac{\partial u_i'}{\partial x_k}\right) \tag{4}$$

Where, *u'*, *v'*, *w'* are the fluctuation values of flow rate in the three directions of *x*, *y*, *z*.

In the standard *k-ε* model， *k* and *ε* are two unkown variables. The corresponding control equation is:

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)= \frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+G_k-\rho\varepsilon \tag{5}$$

$$\frac{\partial}{\partial t}(\rho\varepsilon)+\frac{\partial}{\partial x_i}(\rho\varepsilon u_i)= \frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right]+\frac{C_{1\varepsilon}\varepsilon}{k}G_k-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{6}$$

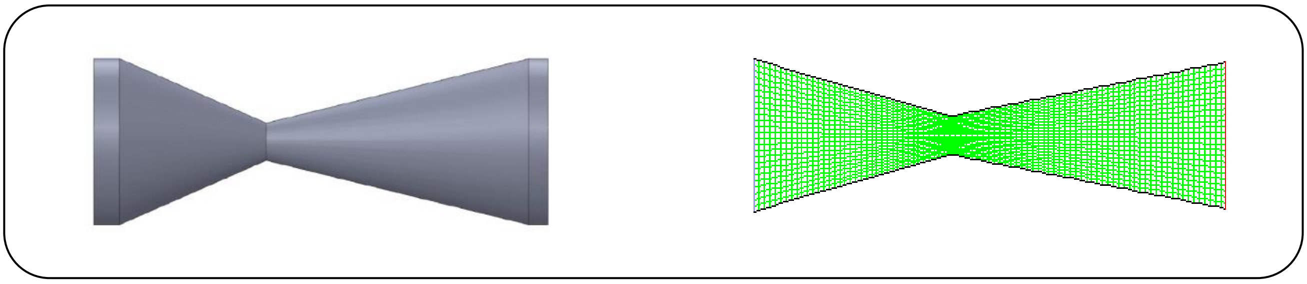

Fig. 3: Venturi 3D image and Venturimesh by Gambit software.

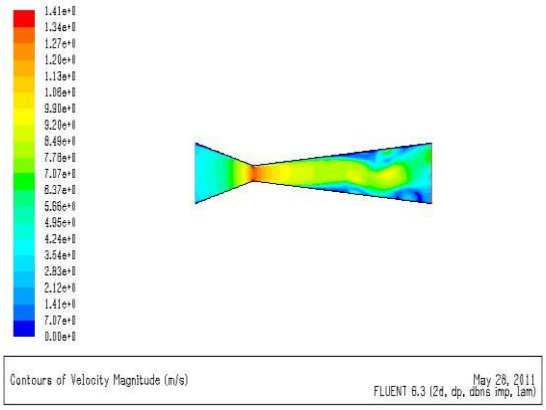

Fig. 4: Velocity contour of venturi 15-5.

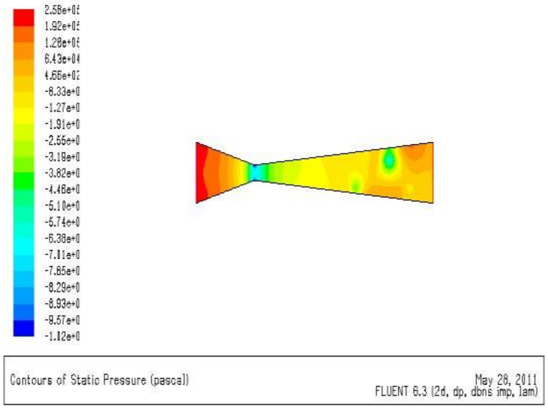

Fig. 5: Pressure contour of venturi 15-5.

Where, μ_t is turbulent viscosity efficient ; G_k is the turbulent kinetic energy k produced by average velocity gradient ; σ_k, σ_ε, $C_{1\varepsilon}$, $C_{2\varepsilon}$areconstants.

RESULT AND DISCUSION

When the pressure at the throat falls below the vapour pressure of liquid, the liquid flashes, generating a large number of cavities which subsequently oscillate and then give rise to pressure and temperature pulses. These pulses cause the better mixing of immiscible liquids and enhanced transesterification process [22].

Fig.4- Fig. 30 provide velocity contour and pressure contour for different geometries of venturi.

The results of the first model with convergence angle of 15 degrees

The inlet pressure for the fluid was considered in all forms of venturi at 3 bars. Three venturi types 15-12, 17-12 and 20-12 were not evaluated due to non-convergence. First, venturi was evaluated at a 15° convergence angle Fig. 4 to Fig. 9, for this convergence angle, there are 3 divergence angles 10°, 7° and 5°.According to the Figs. 4-9, they presented fairly good results for mixing, but in terms of pressure recovery, venture 15-5 had the best recovery compared to the other two structures.

The results of the second model with convergence angle of 17 degrees

For venturi, the convergence angle of 17°, 3 divergence angles were investigated (Fig. 10 - Fig.15). Mixing was better than the 15 degree angle for all three cases. The two angles 5 and 10 had better results than the angle of 7 in terms of pressure recovery. Venturi 17-10 In terms of mixing, retrieval of pressure and homogeneity of points at the outlet had the best results among all designed venturi. Investigating the velocity contour Fig. 14 shows the fluid velocity profile in venturi. As it is known, the cavitation phenomenon has occurred in the throat and the velocity profile was homogeneous across the fluid, which is indicative of the suitability of geometry.According to (Fig.15) (pressure contour), 85% of the input pressure is retrieved, which is acceptable recovery. This venturi was used in a setup laboratory and biodiesel was produced at 95.6% yield. This set-up is

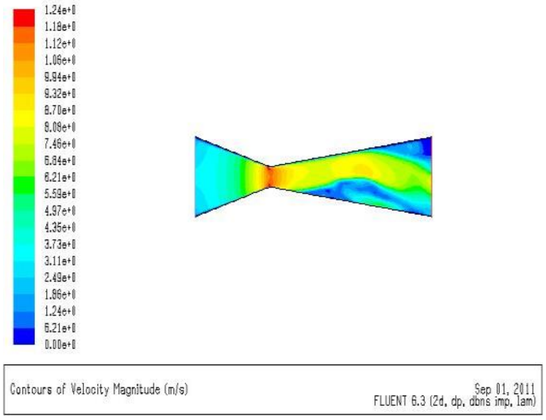

Fig. 6: Velocity contour of venturi 15-7.

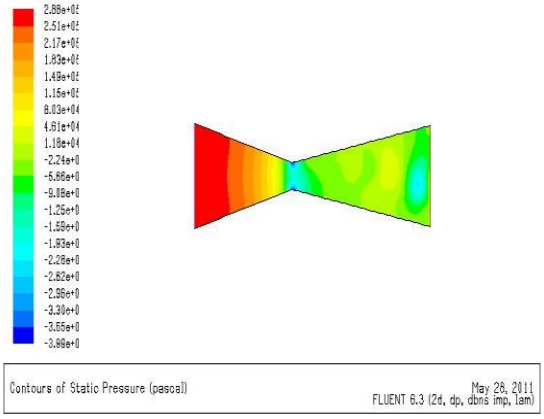

Fig. 9: Pressure contour of venturi 15-10.

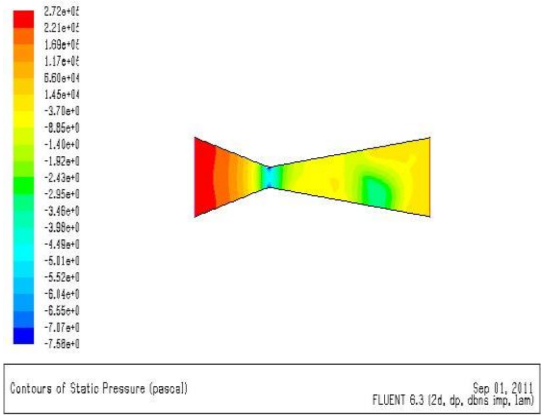

Fig. 7: Pressure contour of venturi 15-7.

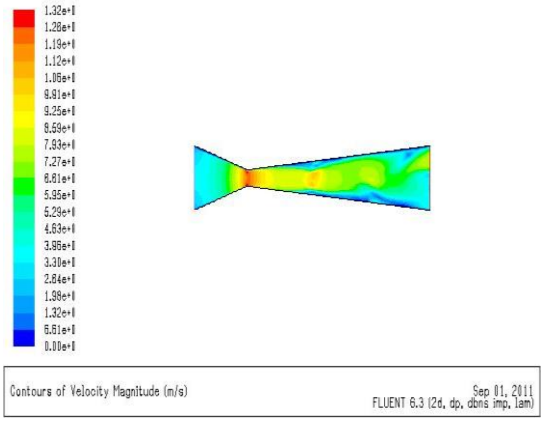

Fig. 10: Velocity contour of venturi 17-5.

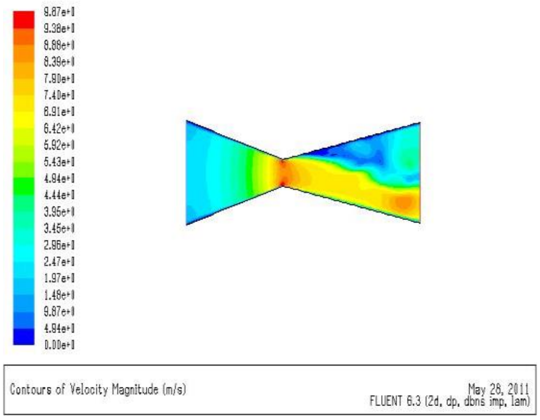

Fig. 8: Velocity contour of venturi 15-10.

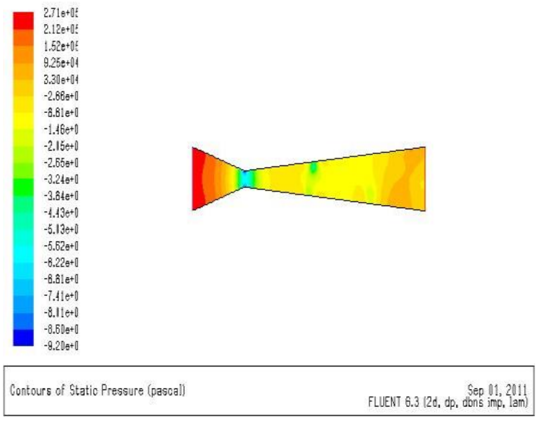

Fig. 11: Pressure contour of venturi 17-5.

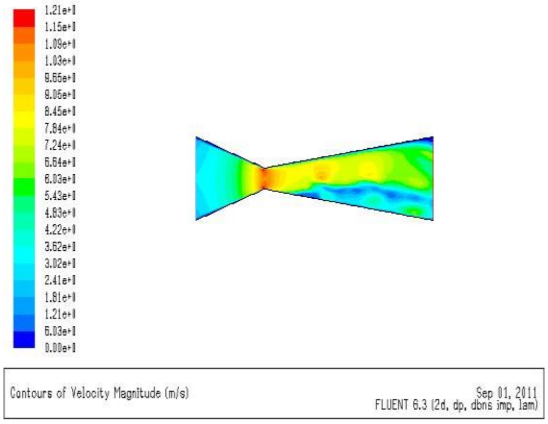

Fig. 12: Velocity contour of venturi 17-7.

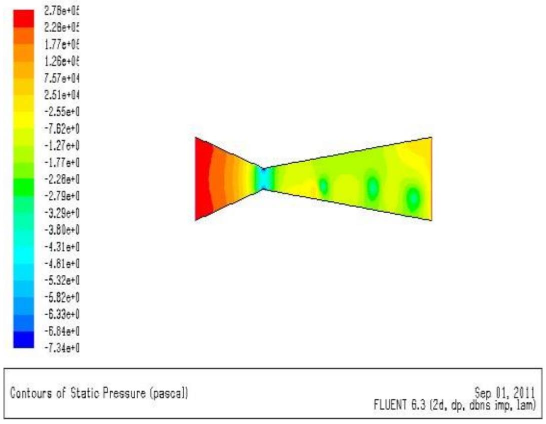

Fig. 13: Pressure contour of venturi 17-7.

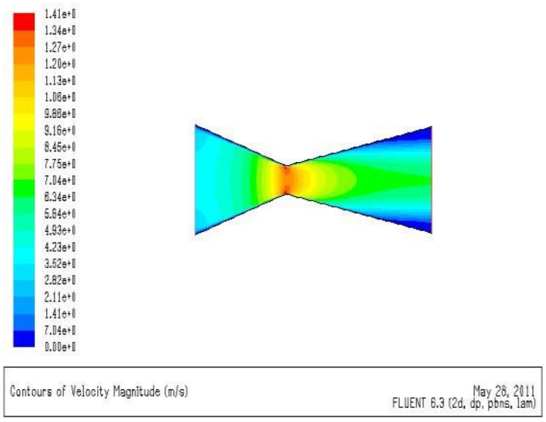

Fig. 14: Velocity contour of venturi 17-10.

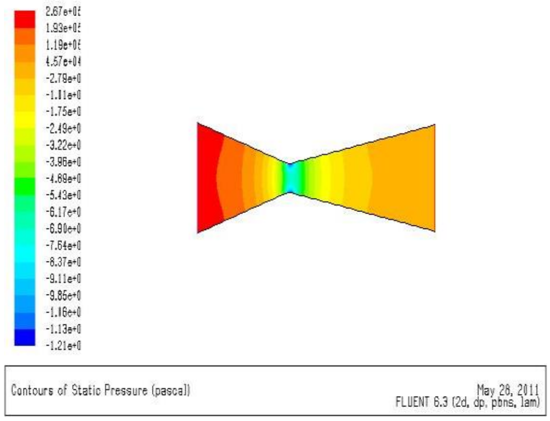

Fig. 15: Pressure contour of venturi17-10.

Fig. 16: Pilot production of biodiesel.

made of stainless steel 316 and has the ability to produce 250 liters of biodiesel per day (Fig. 16).

Pressure was measured on both sides of the venturi by pressure gauges, the value of 3 for the inlet pressure and 2.5 for the outlet pressure, respectively. As a result, we can say that there are over 83% of pressure recovery that fully matches the results of CFD (85%). In addition, the homogeneity of the output of Venturi indicates the proper mixing of compounds, as clearly shown in Fig. 14.

The results of the third model with convergence angle of 20 degrees

Venturi was evaluated with a convergence angle of 20° with 3 divergence angles (Fig. 17- Fig. 22). Out of the three designs for venturi with a 20° convergence

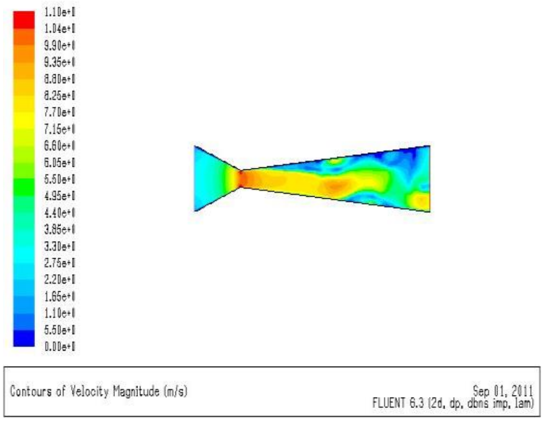

Fig. 17: Velocity contour of venturi 20-5.

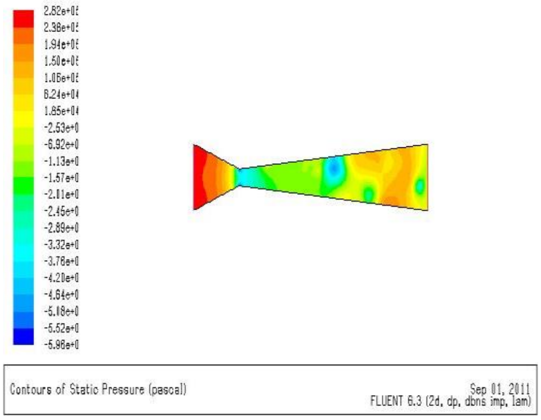

Fig. 18: Pressure contour of venturi 20-5.

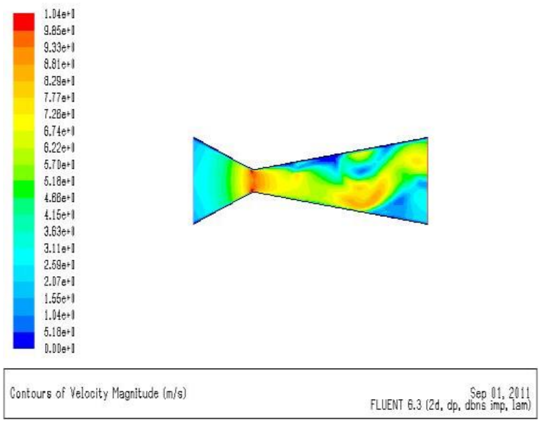

Fig. 19: Velocity contour of venturi 20-7.

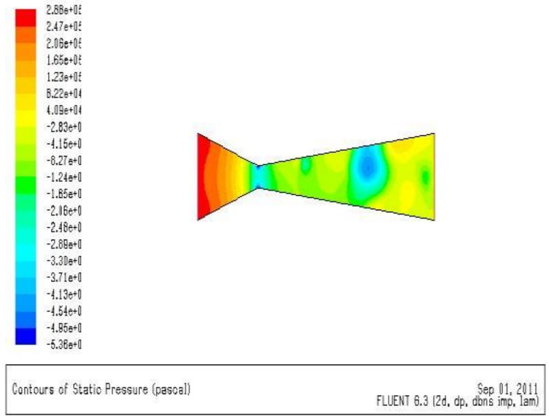

Fig. 20: Pressure contour of venturi 20-7.

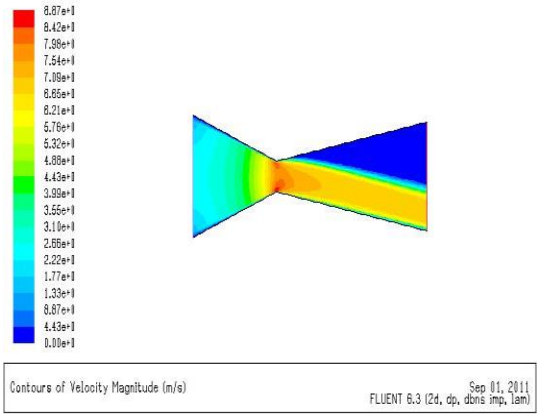

Fig. 21: Velocity contour of venturi 20-10.

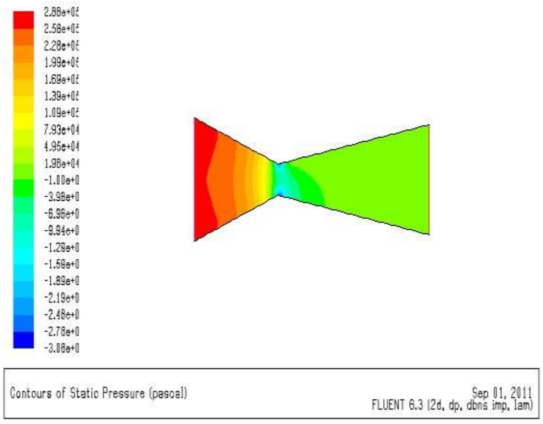

Fig. 22: Pressure contour of venturi 20-10.

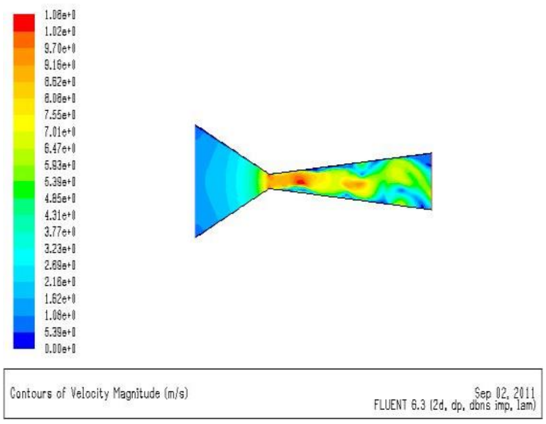

Fig. 23: Pressure contour of venturi 20-7.

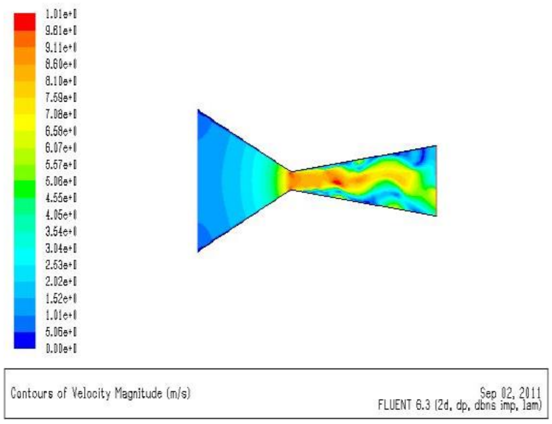

Fig. 25: Pressure contour of venturi 20-10.

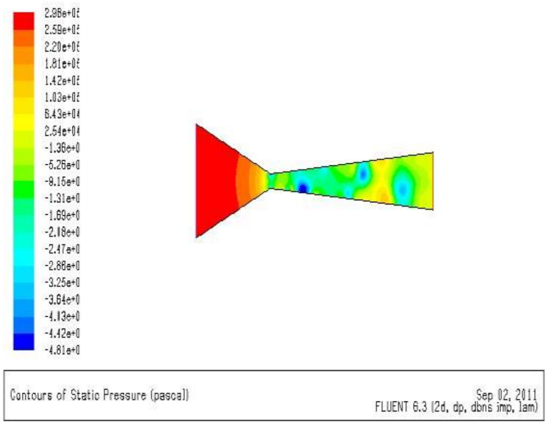

Fig. 24: Velocity contour of venturi 20-10.

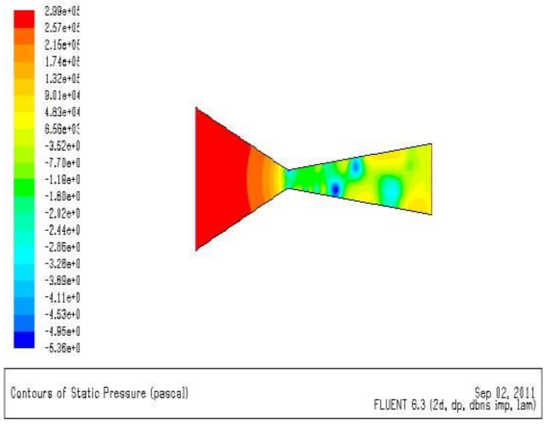

Fig. 26: Pressure contour of venturi 22-7.

angle, venturi 20 - 10 did not provide a satisfactory result due to the unconditioned mixing andinappropriate pressure recovery, but two other models with 5° and 7° divergence angles presented relatively acceptable results, but the results were weaker than venturi with a 17° convergence angle.

The results of the fourth model with convergence angle of 22 degrees

The last convergence angle is 22°.For venturi, the angle of convergence of 22°, four divergent angles were considered (Fig. 23- Fig. 30). Generally, all four designs for this angle did not show good results.At 22° of convergence angle, due to the large slope of the convergence section, high pressure drop occurs, and it is not possible to pressure recovery. Therefore, this angle is not suitable for the biodiesel production system. As a result, according to the description and also the contours obtained by Fluent software, the best design for the biodiesel production system is the venturi 17 -10.

Fig. 31 shows pressure recovery percentage of venturi (different geometry). Two termspressure recovery and cavitation generation for each venturiwas investigated.If the velocity of the fluid in throat reaches tothe Mach number, cavitation is done.Velocity contours show that the velocity in the throat is increased and therefore the pressure is reduced,as a result, when pressure reaches below the vapor pressure of the fluid, cavitation occurs.For all geometries except 22-10 and 22-12, cavitation was generated.

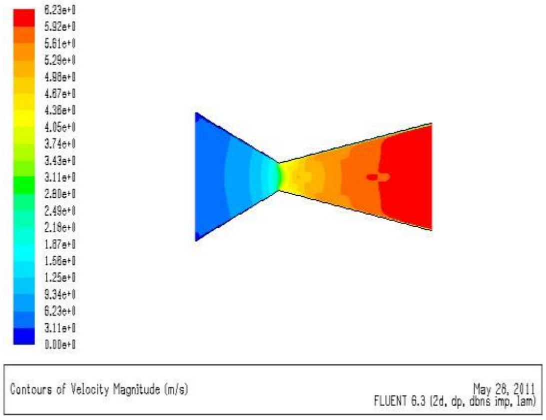

Fig. 27: Velocity contour of venturi 22-10.

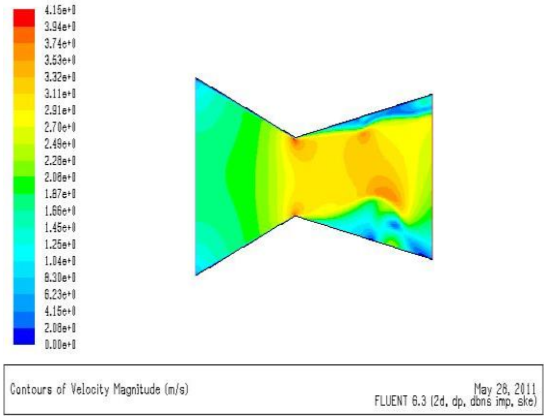

Fig. 29: Velocity contour of venturi 22-12.

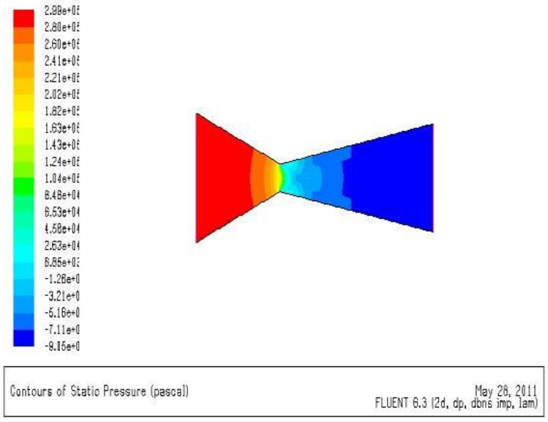

Fig. 28: Pressure contour of venturi 22-10.

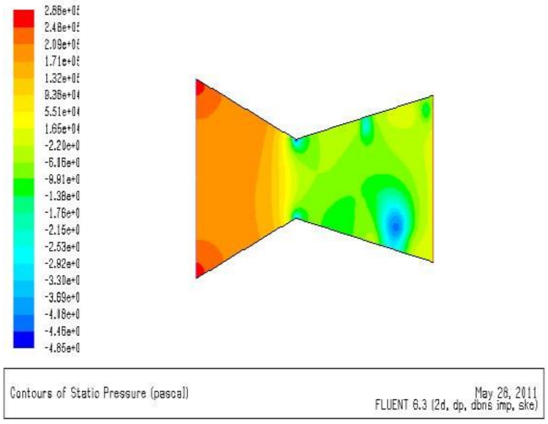

Fig. 30: Pressure contour of venturi 22-12.

Biodiesel Analysis (Produced from Pilot)

To ensure the production of biodiesel, its FT-IR spectrum was studied. In this research, the NICOLET 8700 (USA) was used to get the FT-IR spectrum. According to Fig. 32, the absence of a peak in the area of 3200-3500 cm^{-1} indicates that there is no alcohol and water in the final product.

CONCLUSIONS

Venturi was used as a mixing tool by making cavitation in the biodiesel production system.Hydrodynamic cavitation is one of the intensive methods for eliminating the mass transfer limitation of transesterification reaction. Venturi was designed with different angles in Gambit software and was evaluated in Fluent software.In order to reduce the cost of manufacturing, the results of the Fluent software are first performed for each angleand finally, the best model was introduced.The goal of Venturi's hydrodynamic analysis is to carry out a transesterification reaction with a yield of more than 90%.Venturi was evaluated with convergence angles of 15, 17, 20 and 22 degrees, and the divergence angles of 5, 7, 10, and 12 degrees;threeventurigeometries 15-12, 17-12, and 20-12 were not evaluated due to non-convergence. As a result, according to the description and also the contours obtained by Fluent software, the best design for the biodiesel production system is venturi 17 -10. Venturi 17-10 In terms of mixing, recovery of pressure

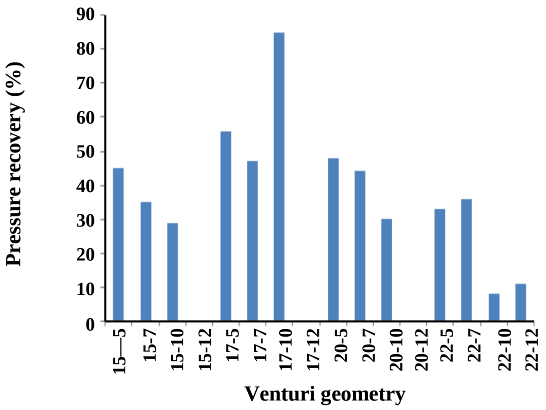

Fig. 31: ***Pressure recovery percentage of venturi(different geometry).***

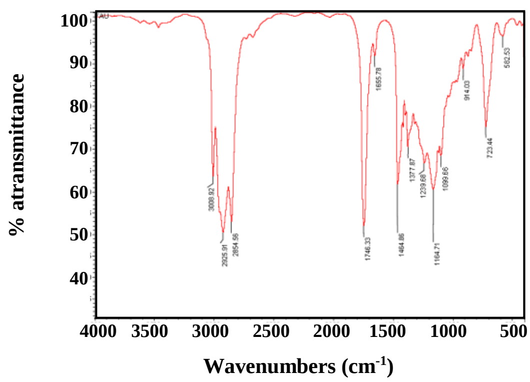

Fig. 32: FTIR spectrum of biodiesel.

and homogeneity of points at the outlet had the best results among all designed venture, so selected for the build.This venturi recovered 85% of the input pressure, also provides a good mixing process to eliminate the mass transfer of oil and alcohol by creating cavitation.CFD results were completely consistent with experimental data. According FTIR spectrum of biodiesel, the absence of a peak in the area of 3200-3500 cm^{-1} indicates that there is no alcohol and water in the final product.

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