NUMERICAL SIMULATION OF MIXING IN A JET AGITATED LARGE HORIZONTAL CYLINDRICAL TANK

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ABSTRACT

Mixing in a fluid jet agitated horizontal cylindrical tank has been simulated using computational fluid dynamics. A known volume of hot fluid is allowed to mix with the main fluid in the large tank which is set at a lower temperature. The fluid jet is provided using a simple pump around. Temperature measurements at various monitoring points inside the tank are used to quantify mixing. Results show that blending time is largely dependent on the flow patterns generated inside the tank. These flow patterns are a function of the tank geometry, the location and the angle at which the jet is injected. The role played by the length of the jet in determining the blending time is not as major as was thought by earlier workers. Significant reduction in blending times is achieved by changing the location and/or the angle of the incoming jet in a way that results in a better flow circulation.

Keywords: *Mixing, jet, numerical simulation, tank*

الملخص

تمت محاكاة الأداء لخلأطات النفث الأرتطامي في وعاء اسطواني افقي. واستعملت الحرارة كمقياس لدرجة الخلط. اظهرت النتائج ان الوقت اللأزم لتحقيق خلط كامل يعتمد على اشكال السريان داخل الوعاء. واظهرت ايضا ان دور طول النافث ليس بالأهمية التي كان يعتقدها بعض الباحثين سابقا. ويمكن خفض الوقت اللازم للخلط بتغيير موضع النافث او زاويته.

1. INTRODUCTION

Fluid jet mixers are used in the process industries to achieve an even distribution of concentration or temperature. Jet mixers consist mainly of a pump around which is a stream taken out from one location in the tank and returned to another location. Jet mixers offer savings in capital, maintenance and operation costs when compared with other mixers such as mechanical mixers.

Mixing and blending times refers to the time lapsed from the instant of the addition of the tracer until the variable measured reaches its equilibrium value. The difference between blending and mixing time can be explained as follows: blending time refers to the case when the tracer is added as the pump-around is started while mixing time is used when the tracer is added after the flow in the tank becomes fully developed. In this paper, blending time is used to quantify mixing.

Researchers have, investigated jet mixing and correlated mixing time with other system parameters, such as jet velocity and diameter, tank dimensions and aspect ratio. Some of these correlations stated that mixing time is a function of Reynolds number while other correlations were independent of Reynolds number. Different techniques, including the measurement of conductivity or temperature, have been employed to examine the performance of jet mixers.

Fox and Gex [1956] indicated that mixing time is dependent on the jet Reynolds number. Other researchers including [Lane and Rice 1982, Malguernera and Suh 1977, Lee *et al*. 1980 and Tuker and Suh 1980] suggested some dependence of mixing time on Reynolds number.

Fosset and Prosser [1949] presented a correlation for predicting mixing time. That correlation shows no dependence on the jet Reynolds number. Many other researchers including [Okita and Oyama 1963 and Coldrey 1978], have adopted a correlation similar to that of [Fosset and Prosser 1949]. Grenville and Tilton [1996] offered an improved correlation of blend time data.

Limited research has been carried out to investigate the flow patterns in a jet mixer. Maruyama [1986] proposed that mixing time is a function of Reynolds number and of the largest free jet length, but also emphasized the role of the flow patterns existing inside the mixing tank on the mixing time behaviour. Lee *et al.* [1980] observed flow structures as a function of Reynolds number. However, the main interest of Lee *et al.* [1980] and Tucker and Suh [1980] was centred on specifying values of Reynolds number below which jet mixing is not effective.

Perona *et al.* [1998] studied jet mixing of liquids in long horizontal cylindrical tanks. Blending times were measured by the use of a sodium chloride tracer and several conductivity probes distributed throughout the tank. Blending times for each tank were correlated with the jet Reynolds number and for two tank sizes of 0.87 m^3 and 95 m^3.

Zughbi and Rakib [2002] developed a computational fluid dynamics model for a jet mixer in which a known volume of a hot fluid is mixed with a larger quantity of cooler fluid. Temperature was the measured variable in order to quantify mixing. The model was validated against the experimental data of Lane and Rice [1982] and an excellent agreement between numerical and experimental results was obtained. Zughbi and Rakib [2001] also found that the blending time, in an upright cylindrical tank, depends on the flow patterns which depend on the angle of the injection of the jet. This finding contradicts that of Okita and Oyama [1963] and highlights a factor that has not been fully considered when studying jet mixers.

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In the present study, mixing in a fluid jet agitated large horizontal cylindrical tank is simulated using computational fluid dynamics (CFD). The tank considered in the present study is similar to that of Perona *et al.* [1998]. Results shed significant light on the velocities field and mixing characterization involved in such jet mixers.

2. MATHEMATICAL FORMULATION

The governing equations for this mixing problem are the mass, momentum and energy equations. In this study, a general purpose computational fluid dynamics (CFD) package, FLUENT, has been used to solve the equations using finite volume approximations. Full details of this model are given by Rakib [2000]. Turbulence has been modelled using the standard k-ε model. Another more sophisticated turbulence models, the Reynolds stress model, has also been tried but gave almost identical results. The k-ε model has been chosen due to savings in computing time.

3. THE NUMERICAL MODEL

A numerical model has been constructed to simulate jet mixing in a tank similar to the one used by Perona *et al*. [1998]. The tank is a horizontal cylinder 0.6 m in diameter and 3.0 m long. A 0.04 m pipe is used to draw liquid from one side of the tank and to return it either to the other side or to somewhere in the bottom of the tank. Figure 1 shows a schematic diagram of this tank. The pump-around arrangement is slightly different from that used by Perona *et al*. [1996]. In this study, mixing is quantified using blending time. Blending time measures the time from the instant of adding the tracer to the time when the value of the measured quantity anywhere in the tank is less than 5% of the step input. The step input is defined as the difference between the initial value and the final mean value. In this study, the 95% blending time, t_{b95}, is defined and used to quantify mixing. As mentioned earlier, for blending time, the tracer is added and the pump is started at the same time when the liquid is quiescent. Other papers may refer to mixing time. In terms of a concentration tracer, m can be defined as:

$$m = \left| \frac{c - \bar{c}}{\bar{c}} \right| \langle \; 0.05$$

Where $\bar{c}$ is the equilibrium concentration and c is the concentration at any monitoring point at any time. When the above condition is met at all monitoring points around the tank, it can then be said that concentration at any point of the tank has reached 95% or more of the equilibrium concentration. For this case the initial value of m before the addition of the tracer is considered to be 0.

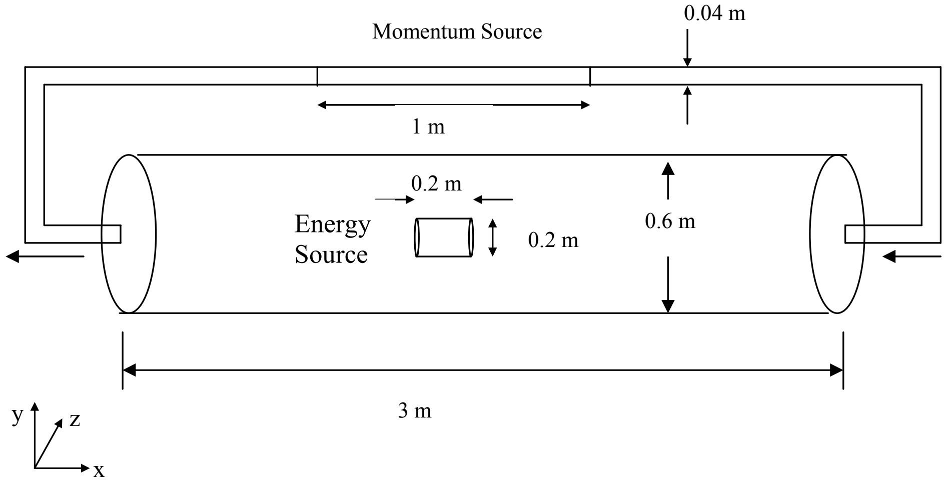

Figure 1: A schematic two-dimensional diagram showing a horizontal cylindrical tank (3 m by 0.6 m) and the inlet and outlet of a fluid jet. The dimensions of a volume that was heated for mixing time calculations are also shown.

In the present study, the whole tank is set initially at 300 °K. A known volume of the liquid (a cylindrical volume 0.2 m in diameter and 0.2 m long) is heated up to 600 °K. Thus the equilibrium temperature can be calculated. The 95% blending is reached when the temperature anywhere inside the tank is within the range of $((\overline{T} \pm (\overline{T} - 300) * 0.05)$. The time required for the hot fluid to blend is then measured according to this criterion which means that the maximum temperature difference between any two points inside the tank should not exceed 0.22 °K. Nine points are used for monitoring mixing as shown schematically in Figure 2.

The pump-around has been simulated by adding a momentum source to the fluid at a plane in the pipe near the outlet. This is similar to a pump. The velocity at the jet inlet is read from the model. The jet Reynolds number Re_j is then calculated as $Re_j=\rho D_j V_j/\mu$ where D_j is the diameter of the jet and V_j is the velocity at the jet inlet.

The temperature is used as an alternative for a massless tracer that travels with the local fluid velocity. Accordingly, density and viscosity are considered not to vary with temperature in the range considered. Thus, the flow field is not affected by the change in temperature.

A tetrahedral mesh has been used to discretize the computational domain. A mesh interval of 15 mm has been used. Tests were carried out with larger mesh intervals including 20, 18, 17, and 16 mm. At 15 mm the solution is found to be independent of the grid size.

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4. RESULTS

Perona *et al*. [1998] recorded their data with a single jet placed about ¼ tank length from one end of the tank and close to the bottom of the tank, pointed towards the centre of the tank. Each test began with the tank containing water in a quiescent condition which means they measured blending time. Figure 1 also shows the position of the momentum source and the initial position of the hot volume. The position of the jet and the angle at which it is injected are varied in this study.

Figure 2 shows the position of the monitoring points used in this investigation. These are located at the four corners of a vertical plane of symmetry (z=0) passing through the jet inlet and outlet and at the four corners of a horizontal plane (y=0) passing through the centre of the tank.

Figure 3 shows the initial (time=0) temperature contours in the vertical plane of symmetry of the tank. The small hot volume at the center with a temperature of 600 K acts as the temperature tracer, with the bulk of the fluid at a temperature of 300 K. Figures 3 and 4 show the temperature contours at time 0, 86, 200 and 374 seconds respectively. At 374 seconds when the temperature range spans a mere 0.175 K, the tank contents are assumed to be well mixed. Table 1 shows the ranges of temperature in each of the contour plots in Figures 3 and 4.

Table 1: Ranges of temperature in the contour plots in Figures 4 through 6

Time in seconds	Minimum Temperature in the whole tank (K)	Maximum Temperature in the whole tank (K)
0	300	600
86	300	309.05
200	300.034	302.9349
374	302.057	302.23

Figure 5 shows the velocity vectors in the vertical plane (z=0) that has been defined earlier. The Reynolds number for this plot is 57324. This Figure shows that the jet diffuse rather quickly and weak circulation is observed in the tank. Figure 6 shows the temperature response at the eight points (points *a* through *h*) under investigation and the jet inlet. The monitoring points *a, b, e* and *f* near the wall of the jet inlet show a slow and steady rise in the temperature until they reach the final equilibrium temperature. In contrast, the other four monitoring points *c, d, g* and *h* at the far end of the tank (opposite the jet inlet) show a rather sharp rise in temperature above the equilibrium temperature and then a decline towards the final equilibrium temperature. This trend agrees with expectations, i.e. points opposite the jet inlet show a similar trend and their temperatures increase quickly because of the strong jet flow in their direction. The temperature of the monitoring points near the wall where the jet is injected

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also show a similar but a different trend to the previous one. Their temperatures increase slowly due to the slow flow in their direction. The similarity of the response of the 2 groups of monitoring points reflects the symmetric location of the jet inlet and outlet.

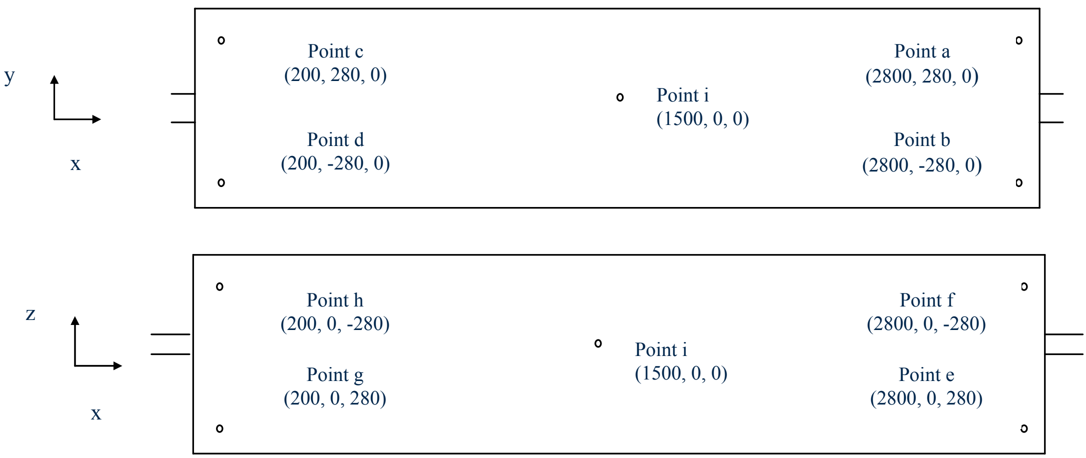

Figure 2: Position of the monitoring points for investigation using the large cylindrical horizontal tank.

To investigate the effects of flow patterns and the position of the jet on blending time, another geometry is used. This geometry is similar to that used in the previous section, except that the jet now enters at the bottom of the tank and not its end, at an angle of 15^{o} at a position one-fourth of the length of the tank from one end. Perona *et al*. [1998], in their investigation, inserted the inlet tube inside the tank so that the jet is injected axially into the liquid from a position of one-fourth length of the tank from one end, hence the location of the jet in this simulated case.

Figure 7 shows the velocity vectors in the plane (z=0). The Reynolds number for this plot is 60230. This figure shows much better circulating flow in the tank as a result of the location and the angle at which the jet is injected. Figure 8 shows the temperature response at the eight points (points *a* through *h*) under investigation and the jet inlet. As expected, the temperature at the points behind the inlet of the jet are the last to show an increase in their values and are also the last to reach the final equilibrium temperature. It should also be noted that the temperatures of the monitoring points in this case showed general trends similar to those shown in Figure 6. The differences in the response of the monitoring points can be clearly explained by the flow patterns. The temperature at monitoring point *b* at the lower back end of the tank took the longest time to reach the equilibrium temperature. This can be explained by looking at Figure 7 which shows that point *b* lies in a zone of very low velocities.

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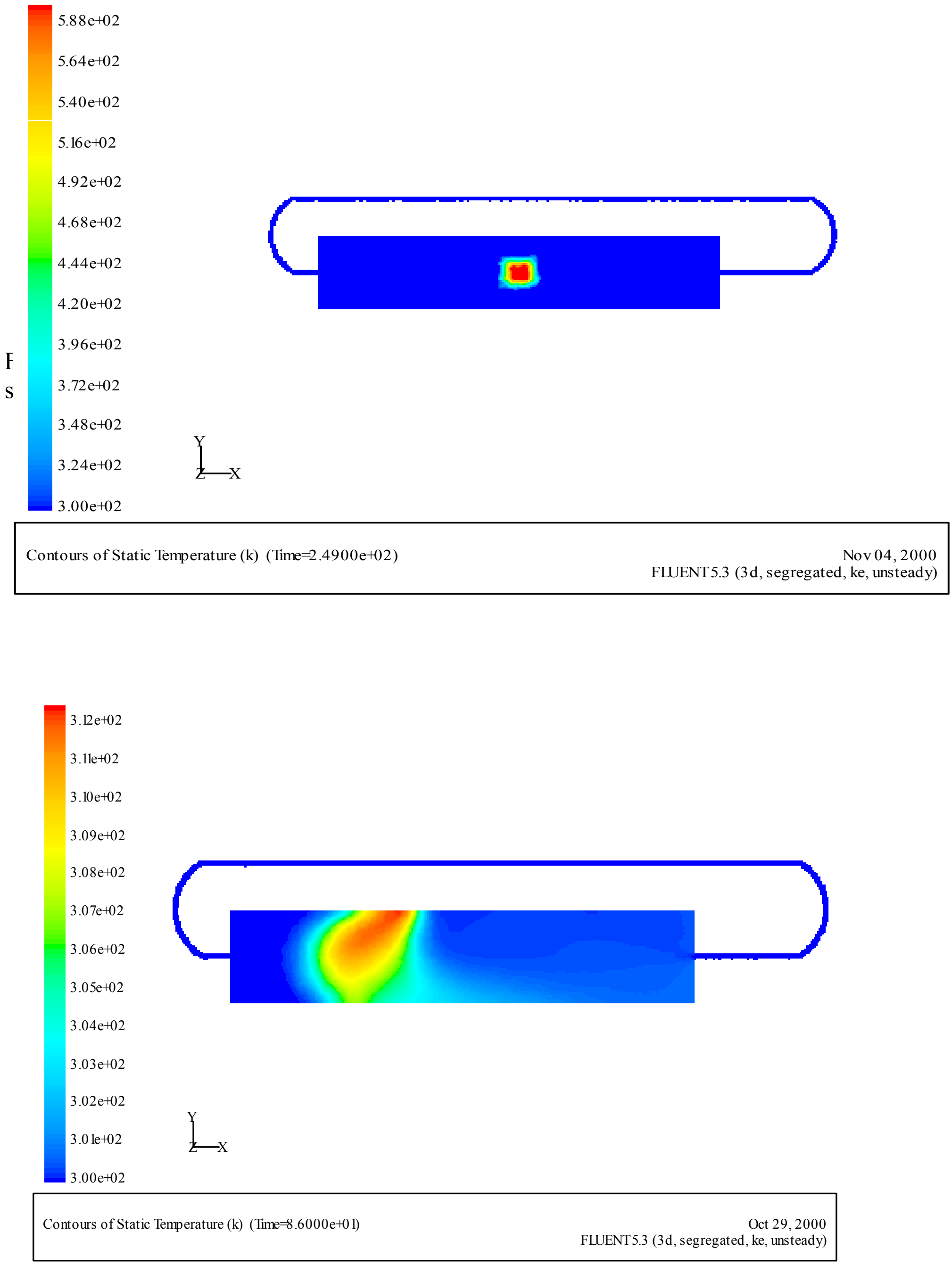

Figure 3: Temperature contours in a plane passing through the jet (z=0) at: (top) 0 seconds and (bottom) 86 seconds. The scales used are not the same with temperature ranges of 105.05 and 12.69 K for the top and bottom plots respectively.

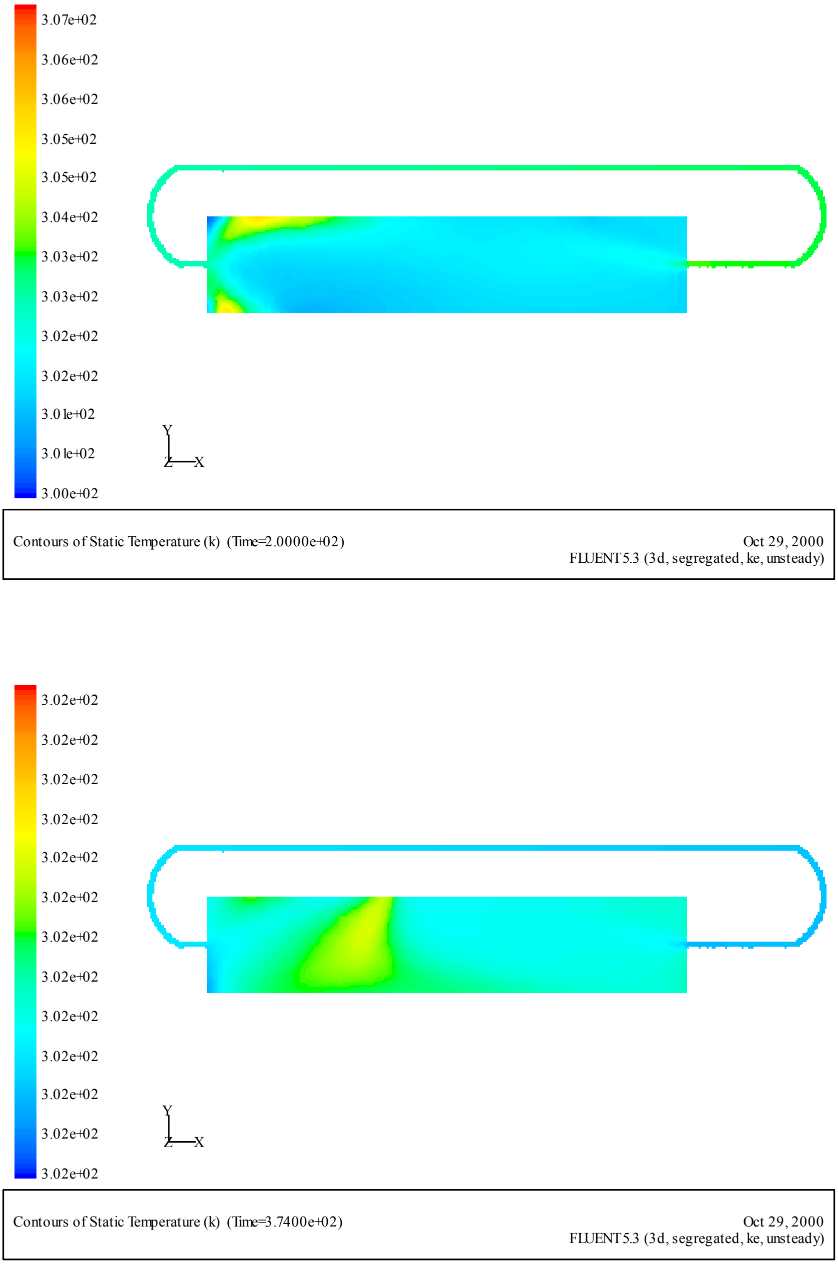

Figure 4: Temperature contours in a plane passing through the jet (z=0) at: (top) 200 seconds and (bottom) 374 seconds. The scales used are not the same with temperature ranges of 7.02 K and 0.175 K (scale is to nearest of 1 K) for the top and bottom plots respectively.

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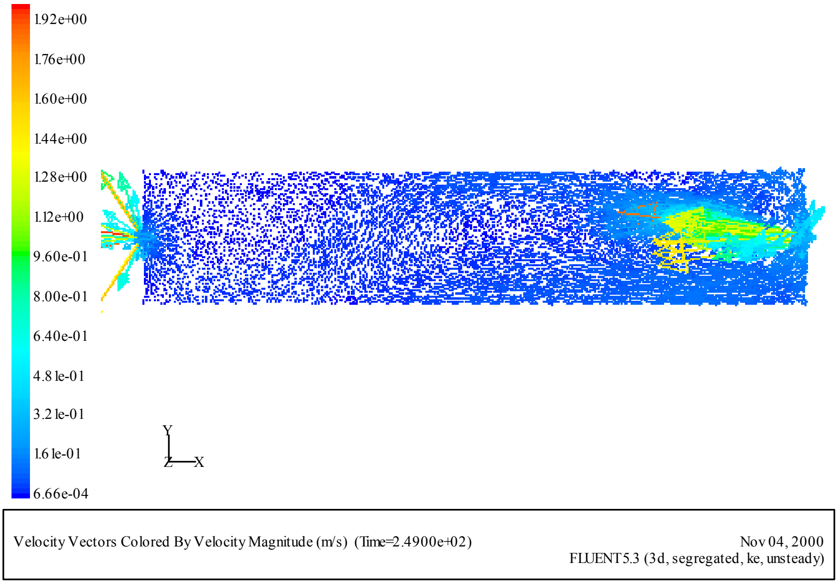

Figure 5: Velocity vectors in a vertical plane (z=0). Some of the vectors representing higher velocity have been excluded for better clarity of vectors inside the tank.

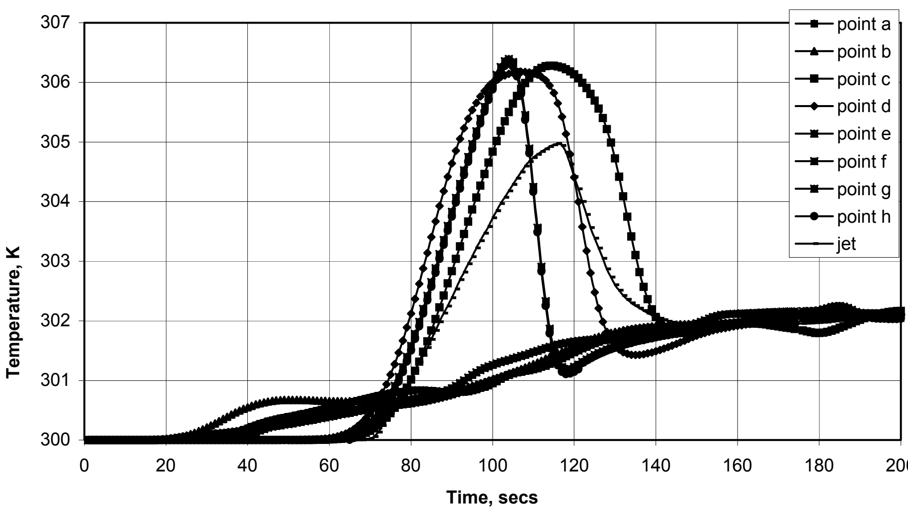

Figure 6: Temperature responses at the eight monitoring points (points *a* through *h*) and at the jet inlet, for a jet inlet at the tank end. The jet Reynolds number for this case is 57324.

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Careful analysis of the two configurations described above shows that the longest time needed for 95% blending is recorded not at monitoring points located in the path of the high convective flow zones, but at those monitoring points located in the so called ‘low velocity zones’. The size and location of these ‘low velocity zones’ depend mainly on the flow patterns generated by the location of the incoming jet. Figure 9 shows the mixing times for these two configurations as a function of the jet Reynolds number. These results show a similar trend to the experimental results of Perona *et al.* [1998], however, the numerical predictions are significantly different from the experimental ones mainly due to the difference in the location of the jet inlet. A comparison of Figures 5 and 7 shows clearly the difference in the flow patters inside the tank as a result of changing the location and the angle of the incoming jet. The overall blending time is largely reduced due to a better flow pattern (stronger circulation) throughout the bulk, as compared to axial injection from one end of the tank for the same jet Reynolds number. The reduction in the mixing time has been found to be even as high as 100%, for example at a jet Reynolds number of 57324.

The trend in the values of the blending time can be explained by the position of the jet. The position of the incoming jet used in the experiments of Perona *et al.* [1998] resulted in a relatively longer blending time. This is mainly due to the zone behind the jet. The two locations used in the simulations are more likely to produce better flow patterns and smaller zones with little flow and consequently shorter blending time.

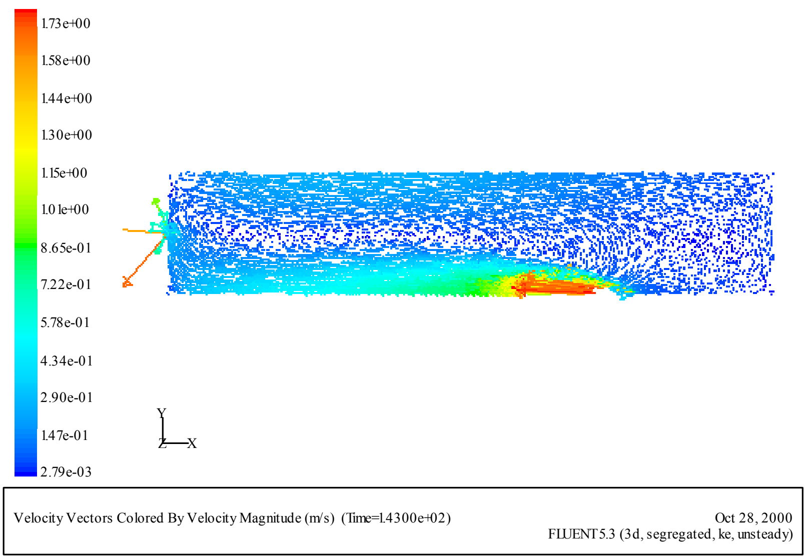

Figure 7: Velocity vectors in a vertical plane (z=0). Some of the vectors representing higher velocity have been excluded for better clarity of vectors inside the tank.

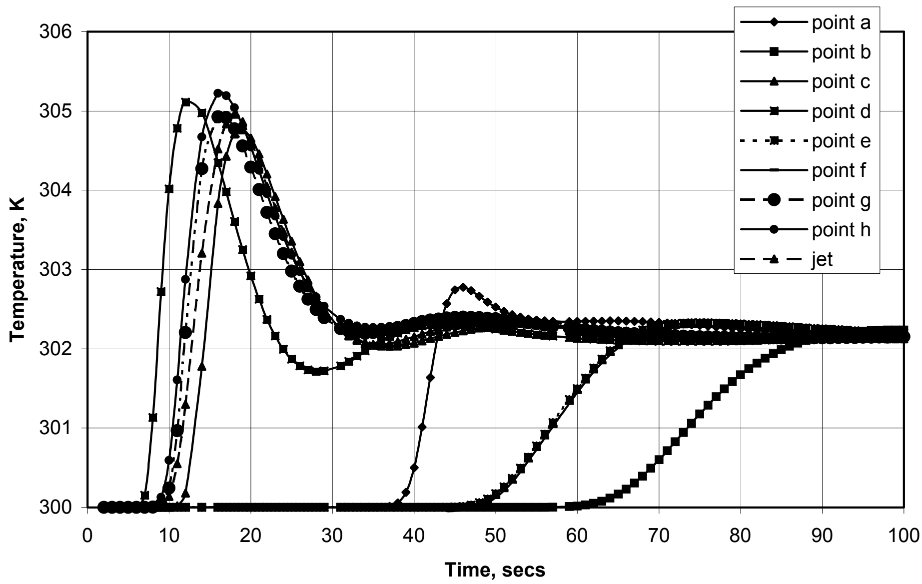

Figure 8: Temperature responses at the eight monitoring points (points *a* through *h*) and at the jet inlet, for inlet at the bottom side of the tank. As expected, points *e*, *f* and *b* are the last ones to respond to the temperature tracer. The jet Reynolds number for this case is 60230.

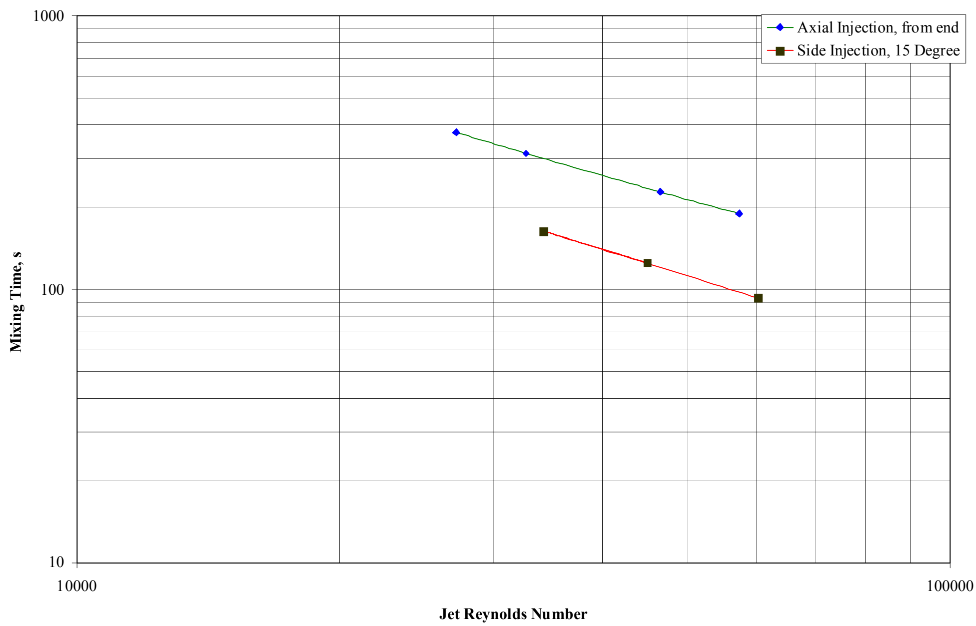

Figure 9: A plot of blending time versus jet Reynolds number for a large cylindrical horizontal tank.

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This study shows that numerical simulations of blending in a fluid jet agitated tank is an effective tool to investigate blending and that simulations can also be a source of significant insight into the process. Results show that ultimately, an equilibrium value of the tracer is established throughout the whole tank. In contrast, it should be mentioned that the sample plot of solution conductivities presented in Figure 2 of Perona *et al.* [1998] shows 2 zones of different conductivities in the same jet agitated tank. This can be explained only if there exists 2 separate zones in the tank where mixing cannot produce the same homogeneous conductivity over the whole tank regardless of mixing duration. This is very unlikely to occur in a jet agitated tank.

It should also be mentioned that Perona *et al.* [1998] mentioned that attempts to obtain mixing times with double direction jets were not successful as the results were chaotic and not reproducible. The authors' simulation experience shows that such a situation may arise only if the jets are unstable especially if there is jet-jet interaction. Simulation of mixing in a much smaller tank (0.3 m in diameter and 0.3 m high) was carried out successfully when two opposing jet were used.

Empirical correlations suggested by Grenville and Tilton [1996], Fox and Gex [1956] and Fosset and Prosser [1949], were not successful in predicting the blending time for the experiments by Perona *et al.* [1998], mainly because the aspect ratio or other tank parameters were outside the recommended ranges for those correlations. This adds to the potential benefits of CFD simulations of fluid jet mixers.

5. CONCLUSIONS

Numerical simulation of mixing in a large horizontal cylindrical tank showed that blending time is a function of the flow patterns generated inside the tank by the jet. Consequently, the jet location is very important in determining the blending time, not so much due to its length but mainly due to the patterns of flow it creates inside the tank. Numerical results showed a similar trend to experimental results published by Perona *et al.* [1998]. However, significant differences in the values of blending time was observed as a result of differences in the flow patterns inside the tank. The differences in the flow patterns were a direct result of varying the location and the angle of the incoming jet. Numerical simulations proved to be a valuable tool to further the understanding of the mixing process and also for optimization purposes. Empirical correlations postulated by earlier researchers were not successful in predicting the blending time for this case. Significant reduction in blending time was achieved by changing the location of the fluid jet. This reduction could reach 100% of the time measured by Perona *et al.* [1998].

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6. ACKNOWLEDGEMENT

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