TIME-FREQUENCY ANALYSIS OF THE FLOW IN A TEE JUNCTION – CONSIDERING MESH RESOLUTION AND *SMAGORINSKY CONSTANT*

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Abstract. *Turbulent flows have been the objective of important studies to discover its dynamics. One important characteristic of these flows is the multiplicity of scales, since the large structures (low frequencies) controlled by the geometry that generates them, until the small structures (high frequencies) limited by the fluid viscosity. In this context, the objective of this work is to study a reference problem (“benchmark”). This problem is an air mixer with different temperatures in a tee junction producing experimental results to validate turbulence model LES (Large Eddy Simulation) implemented at CFX® commercial software. Experimental tests with two different air temperatures inlets were done at the LETeF laboratory. The measures of temperature were acquired with thermocouples installed along the pipe. Relating to numerical tests, the influence of Smagorinsky constant and mesh refining were analized. The emphasis is to describe a large scale turbulence phenomenon. Furthermore, tools capable to compare numerical and experimental data were investigated. The development of signal analysis techniques capable of better describing the phenomenon studied were equally part of the objectives. These techniques must compare temperature fluctuations from experimental data with numerical results to characterize the existence and the shape of turbulent structures with large scales . Preliminary studies of the flow show encouraging results obtained by time-frequency technique.*

Keywords: *time-frequency analysis, large eddy simulation, turbulence.*

1. INTRODUCTION

The analysis of the flow is an extremely important activity in technological areas because many equipments and industrial systems involve liquids and gases for its work or its manufacture. The majority of flows found in nature and in practical applications are turbulent with a complex chaotic behavior. They also are unstable and contain fluctuations that are time dependent and spatial position dependent.

One example of turbulent flow is the oxygen and fuel mixture process into a combustion chamber where the small scale of turbulence makes the mixture more efficient by increasing the engine performance and improving the pollution effects caused for toxic gases released by cars and airplanes. Other important examples are the atmospheric phenomena such as hurricanes and tornadoes that can cause catastrophes where they occur.

The turbulent flows have many features. They increase the propagation power of a flow, producing a more efficient mixture of mass, energy and momentum. Turbulence only occurs in rotational and three-dimensional flows. The solutions for turbulent flows are unpredictable. This is caused by imperfections in mathematical models and methods for solving the equations and because measures used as initial conditions for these simulations are not accurate.

Besides, the important features of a turbulent flow are: energy spectra, which must have a large frequency band or wave length; high Reynolds numbers; and multiple scales, where large structures (low frequencies) are controlled by the geometry that generates them, and the small structures (high frequencies) are limited by the fluid viscosity.

For most engineering applications and even for a phenomenological point of view, the accurate determination of position and phase of a vortex is not essential. The knowledge of statistical parameters of the flow is enough for most of engineering applications. By this way, it is not possible to repeat accurately the experimental results by numerical simulations, i.e., the vortices from numerical simulations not represent exactly the ones observed in an experimental set up, considering spatial position and time, even using very similar initial and limit conditions.

In this context, techniques to compare experimental data with numerical simulations results and help the characterization of existence and the shape of these turbulent structures are extremely important to control or avoid these structures. In what concerns techniques for turbulence study, time frequency and time-scale (wavelets) analysis were applied successfully to a variety of technological and scientific problems.

Using time-frequency analysis, Seleghim (1996), and Seleghim and Hervieu (1998) developed an objective indicator for two-phase flow pattern transition and the unstationarity degree of a signal. It was done independently of the transition or physical variable considered by joint time-frequency covariance associated to a Gabor transform. They concluded that flow pattern transition and unstationarity of a signal or process are characterized by high values of time-frequency covariance.

Later, Tiago and Seleghim (2006) investigated reference problem ("benchmark"). This problem is an air mixer with different temperatures in a tee junction producing experimental results to validate turbulence model LES (Large Eddy Simulation) and DES implemented at CFX® commercial software. In the work it was fixing the same time step, mesh resolution and Smagorinsky constant at 0.1. These computational results were compared with the experimental data through the time-frequency analysis. Studying the flow showed vortices transition regions, and the ability of the time-frequency analysis technique in characterizing the existence and the form with large vortices of the turbulent structures.

In the context of numerical simulation for turbulence studies, Matos et al. (1999) applied Large Edge Simulation for turbulent flows over a two dimensional cavity using Smagorinsky model. Anjorin et al. (2003) investigated experimentally and numerically the dispersion of powder from a pipe by CFD Aflow software using k-ε e RNG k-ε turbulence models. Itai et al. (2006) analyzed the three-dimensional effects of the flow in a channel with curved walls in a wind tunnel. They used the code Fluent and they tested three turbulence models, k-ε, RNG k-ε and RSM.

Recently Goulart, et al. (2004) investigated numerically and experimentally the flow inside a tube bank by CFX software using LES and k-ε models. The reference flow was an air mixer in a tee junction which has a very simple geometry but produces a flow with vortices transitions. Many authors have been studying the flow in a tee junction because it is considered a fast and efficient mixer. We can evoke Maruyama et al. (1981) that investigated experimentally a pipeline mixing between two fluid streams; Tosun (1987) studied micromixing in tee mixers considering different pipeline diameters and Chapuliot et al. (2005) presented a hydro-thermal-mechanical analysis of thermal fatigue in a flow with mixture zones. Besides Hu and Kazimi (2006) utilized code Fluent to study temperature fluctuations in a mixing tee junction of the same diameter were performed using LES. The calculated normalized mean temperatures and fluctuating temperatures are generally in good agreements with measurements.

2. EXPERIMENTAL TESTS

The experimental tests were done at Thermal and Fluid Engineering Laboratory at University of São Paulo at São Carlos. A PVC pipe was assembled with two inlets and one outlet as indicated in Fig.1 to produce an air flow. The thermocouples, type K, were accordingly shielded and they were installed in the outlet direction. The first thermocouple was placed in the center of the tee, the second was placed 0.20 m after the first one, the third was placed 0.20 m after the second one and so on, until the eighth thermocouple.

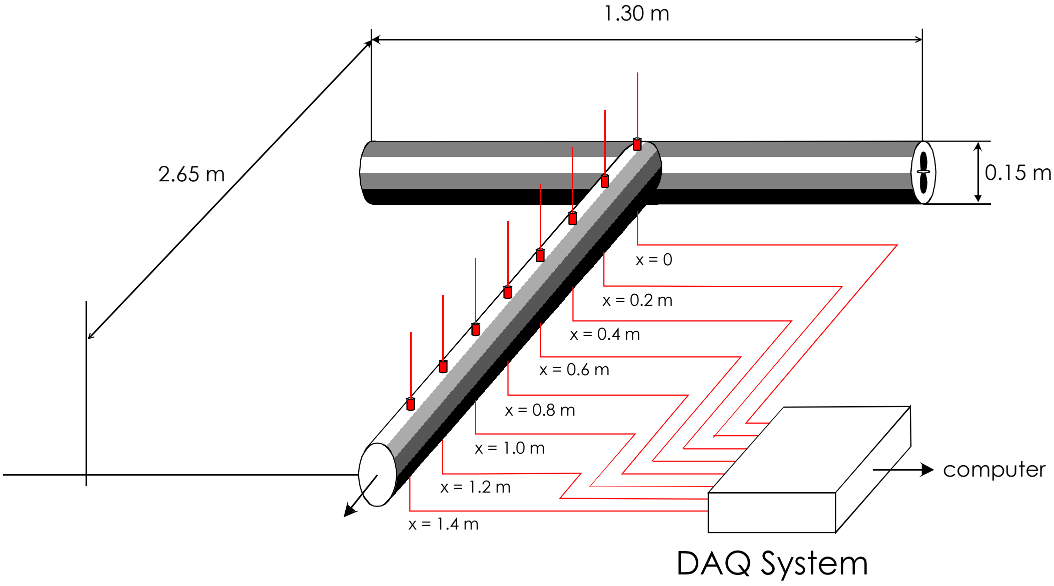

Figure 1. Experimental setup.

Fans were installed in the two inlets in order to control the air flow rate. In one inlet was also placed a shielded resistance to produce the hot air stream. Theses fan were capable to produce velocities of 2.2 m/s in each inlet, and the resistance dissipated 90W. A measure using a thermometer in the two inlets was done. In one side we considered the temperature as room temperature and in the other side the temperature was higher and oscillatory. Because of this we decided to consider average temperature.

Besides the thermocouples, the circuit is provided with a National Instruments acquisition system. The acquisition system was composed of PXI-1000B Chassis equipped with a NI 8176 PXI Embedded Controller (Pentium III 1.26 GHz) and a PXI-6025E Multifunction I/O Board for 200 kS/s 12-bit samplings.

A LabVIEW® program was developed for acquisition and data storage. When number of points was enough to compare with numerical data the acquisition was stopped, i.e., 32768 points. This program allowed choosing the number of sampled point per second and the use of a Butterworth low-pass filter (at 30 Hz) to avoid a 60 Hz external noise. The aliasing effect caused by high frequencies was further eliminated setting the acquisition in a very high frequency, 1000 points per second.

3. NUMERICAL SIMULATION

The commercial software CFX® (version 5.7) was used for numerical simulations considering large scale method: LES. The set of equations solved are the unsteady Navier-Stokes equations in their conservation form. The finite volume method is adopted for numerical discretisation (Patankar, Taylor e Francis, 1980; Versteeg e Malalasekera, 1995).

Continuity Equation: $$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho U_i)}{\partial x_i} = 0 \tag{1}$$

Momentum Equations: $$\frac{\partial \rho U_i}{\partial t} + \frac{\partial (\rho U_j U_i)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \mu \frac{\partial^2 U_i}{\partial x_j \partial x_j} + S_M \tag{2}$$

Thermal Energy Equation: $$\frac{\partial \rho h}{\partial t} + \frac{\partial (\rho U_j h)}{\partial x_j} = \frac{\partial^2 (\lambda T)}{\partial x_j \partial x_j} + S_E \tag{3}$$

A 3.0 GHz Pentium based PC with Linux RedHat was utilized for simulations. Each simulation took about 20 days.

3.1. Large Eddy Simulation Model

Large Eddy Simulation (LES/Smagorinsky) (Smagorinsky, 1963) is about filtering of the equations of movement and decomposition of the flow variables into a large scale (resolved) and a small scale (unresolved) parts. The characteristic filter length determines the cutoff frequency.

Any flow variable f can be written such as:

$$f = \overline{f} + f' \tag{4}$$

where $\overline{f}$, the large scale part, is defined through volume averaging as:

$$\overline{f}(x_i, t) = \int_{vol} G(x_i - x'_i) f(x'_i, t) dx'_i \tag{5}$$

$G(x_i - x'_i)$ is the filter function (called the hat filter or Gaussian filter). Specifically, the function considered in this work is:

$$G(x_i) = \begin{cases} \frac{1}{\Delta^3}, \text{ se } |x_i| \leq \frac{\Delta}{2} \\ 0, \quad \text{se } |x_i| > \frac{\Delta}{2} \end{cases} \tag{6}$$

where Δ is the characteristic filter length.

The filtered Navier-Stokes equations becomes:

$$\frac{\partial (\rho \overline{U}_i)}{\partial t} + \frac{\partial (\rho \overline{U}_i \overline{U}_j)}{\partial x_j} = -\frac{\partial \overline{p}}{\partial x_i} + \mu \frac{\partial^2 \overline{U}_i}{\partial x_j x_j} - \frac{\partial \rho \tau_{ij}}{\partial x_j} \tag{7}$$

where $\overline{U}_i$ is the velocity in the i-direction with spatial filter, $\overline{p}$ is the filtered pressure and τ_{ij} is the sub-grid Reynolds stress defined as:

$$\tau_{ij} = \overline{U_i U_j} - \bar{U}_i \bar{U}_j \tag{8}$$

The sub-grid Reynolds stress is assumed through Smagorinsky model as:

$$\tau_{ij} = -\frac{1}{3}\tau_{kk} = -2 \cdot \nu_{SGS} \cdot \bar{S}_{ij} = \nu_{SGS} \cdot \left(\frac{\partial \bar{U}_i}{\partial x_j} + \frac{\partial \bar{U}_j}{\partial x_i} \right) \tag{9}$$

where ν_{SGS} is the sub-grid scale viscosity expressed as:

$$\begin{cases} \nu_{SGS} = (C_S \Delta)^2 \left|\bar{S}\right| \\ \left|\bar{S}\right| = \sqrt{2\bar{S}_{ij}\bar{S}_{ij}} \end{cases} \tag{10}$$

For practical calculations the value of C_S is changed depending on the type of flow and mesh resolution. A study about the influence of this constant is considered in this work. The values of C_S of 0.07, 0.1, 0.18 and 0.2 were adopted.

The turbulence characteristic length is calculated by:

$$k = \frac{3}{2} I^2 U^2 \tag{11}$$

$$\varepsilon = \rho C_\mu \frac{k^2}{\mu_t} \tag{12}$$

$$L_t = \frac{\sqrt{k^3}}{\varepsilon} \tag{13}$$

where I is the turbulence intensity ranging from 0.001 to 0.1 (i.e 0.1% to 10%), corresponding to very low and very high levels of turbulence in the flow respectively. C_μ is a k-ε model constant and its value is 0.09.

3.2. Geometry and numerical discretisation

Geometry with the same dimensions and features of the experiment was assembled for numerical simulations as shown in Fig. 1. Considering in numerical simulations a flow starting as an established flow regime, the part containing the resistance and the fans was disregarded. This fact changed the distance between the inlets from 1.3 m to 1.0 m.

The software allows the use of monitoring points inside the flow. It was done representing the exact position of thermocouples and the temperature in each point was monitored. The mesh in all cases was tetrahedral and unstructured. The mesh resolution were varied: intermediary (34169 nodes and 99307 elements); coarse (19945 nodes and 53940 elements); fine (73773 nodes and 237322 elements).

The fluid used was Air at 25°C with thermophysics properties (viscosity and density) considered as constants at 25°C and 1atm. In both inlets was specified a 2.2 m/s normal velocity at the boundary and a static temperature. In one side was specified a hot temperature and in the other a cold temperature.

Despite turbulence intensity has no physical meaning in LES model, the software allowed this set up, and then tests were performed considering 1% and 0.5% in order to verify its influence. Probably, this turbulence intensity is acting as a numeric noise for the two entrances of the flow. In the recent software version, CFX® (10.0), this bug was already corrected.

The pressure in the outlet was specified as the atmospheric pressure. The time step was constant at 0.001s in order to achieve the same frequency as the experiment. The simulation total time was defined to totalize 32768 (= 2^{15}) temperature points, i.e., about 33 seconds.

A heat transfer model is used to predict the temperature throughout the flow. Specifically the Thermal Energy model was selected. The heat transfer at the walls was considered as adiabatic. The buoyancy force was not considered. The walls were impermeable, limited, smooth and non-slip.

4. SIGNALS ANALISYS

The signals from thermocouples installed along the pipe and monitoring points in the numerical simulations were analyzed aiming basics proprieties characterization. The method used for comparisons was the joint time-frequency analysis.

4.1. Time-frequency Analysis

The main idea of time-frequency analysis is to understand situations where the signal frequency composition changes with time. The objective of time-frequency analysis is to discover a function which describes the energy density of a signal simultaneously in time and in frequency. By this function, it is possible to know the energy fraction in a specific time or frequency band. It is also possible to calculate the frequency distribution in certain time, global momentum, local momentum etc.

In order to investigate the signal proprieties in a time of interest, t, we emphasize the signal at this time and suppress it for times far away from that time. According Cohen (1995) it is done by multiplying the signal by a window function h(t) producing a modified signal. Denoting the signal as s(t), the current time as τ, and the modified signal as $s_t(\tau)$ then:

$$s_t(\tau) = s(\tau)h(\tau - t) \tag{14}$$

Since the modified signal emphasize the signal around the time t, the Fourier Transform will produce the frequency distribution around this time with frequency ω :

$$s_t(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} e^{-j\omega\tau} s_t(\tau) d\tau \tag{15}$$

$$s_t(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} e^{-j\omega\tau} s(\tau)h(\tau - t) d\tau \tag{16}$$

The energy density spectrum at time, t, is:

$$P_{sp}(t,\omega) = \left|s_t(\omega)\right|^2 = \left| \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{+\infty} e^{-j\omega\tau} s(\tau)h(\tau - t) d\tau \right|^2 \tag{17}$$

Thus, for each time, t, we have an energy density spectrum and by jointing these densities we have the time-frequency distribution $P_{sp}(t,\omega)$. We can construct $P_{sp}(t,\omega)$ by the short time Fourier transform or the Gabor's transform among others. In this work the joint time-frequency function was obtained by Gabor's transform which consider the Gaussian function as the window function $h(\tau - t) = e^{-\alpha(\tau - t)^2}$. The statistical functions utilized in this work were time-frequency covariance and energy of $P_{sp}(t,\omega)$ calculated for constant air flow rates.

Considering the frequency limits, F_{min} and F_{max}, the time limits, T_{min} and T_{max}, the energy E which characterizes the system instability is given by:

$$E = \int_{F_{min}}^{F_{max}} \int_{T_{min}}^{T_{max}} P_{sp}(t,\omega) dt d\omega \tag{18}$$

The time-frequency analysis is a powerful tool to evaluate the stationarity of a signal or process. In the context of deterministic processes, the stationarity is assumed as a spectral state in which the frequency composition is independent of time (Seleghim and Hervieu, 1998). However, real signals are never purely stationary and a more realistic attribute describing the steadiness of the spectral content is their degree of unstationarity.

The covariance considered in this work quantifies how time is correlated with frequency. Thus the covariance is equal to zero when frequency does not change with time. A high covariance indicates a high degree of unstationarity of a signal and the frequency changes more with time (Cohen, 1995 and Lathi, 1968).

Thus if time and frequency are not correlated it is possible to say that $P(t,\omega)$ is a separable (or factorable) function,

$$P(t,\omega) = F(t)G(\omega) \tag{19}$$

Considering a particular time in time-frequency distribution, τ, and defining an accurate time for analysis, T, a centered time, $\Delta_t(\tau)$, a centered frequency, $\Delta_\omega(\tau)$, and a mixed moment, $\Delta_{t\omega}(\tau)$:

$$\Delta_t(\tau) = \frac{1}{E(\tau)} \int_{-\infty}^{+\infty} \int_{\tau-\frac{T}{2}}^{\tau+\frac{T}{2}} tP(t,\omega)dtd\omega \tag{20}$$

$$\Delta_\omega(\tau) = \frac{1}{E(\tau)} \int_{-\infty}^{+\infty} \int_{\tau-\frac{T}{2}}^{\tau+\frac{T}{2}} \omega P(t,\omega)dtd\omega \tag{21}$$

$$\Delta_{t\omega}(\tau) = \frac{1}{E(\tau)} \int_{-\infty}^{+\infty} \int_{\tau-\frac{T}{2}}^{\tau+\frac{T}{2}} t\omega P(t,\omega)dtd\omega \tag{22}$$

Let $\sum(\tau)$ a centered interval in τ with duration T, and E(τ) the total energy:

$$\sum(\tau) = \left[\tau - \frac{T}{2}, \tau + \frac{T}{2}\right] \tag{23}$$

$$E(\tau) = \int\int_{\sum(\tau)} P(t,\omega)dtd\omega \tag{24}$$

If the original signal is stationary, it is reasonable to assume that these averages are uncorrelated. Under the assumption above:

$$\Delta_{t\omega}(\tau) = \Delta_\omega(\tau)\Delta_t(\tau) \tag{25}$$

Therefore the excess of $\Delta_{t\omega}(\tau)$ over $\Delta_\omega(\tau)\Delta_t(\tau)$ quantifies how time is correlated with frequency. Thus, the time-frequency covariance is defined as (Seleghim e Hervieu, 1998):

$$\mathrm{cov}_{t\omega} = \left|\Delta_{t\omega}(\tau) - \Delta_\omega(\tau)\Delta_t(\tau)\right| \tag{26}$$

We can verify that if $P(t,\omega)$ is separable, i.e., $P(t,\omega) = F(t)G(\omega)$, then the covariance equals to zero.

5. RESULTS

The list of experiments is shown in Tab. 1. In this table are included the room and heated temperatures (°C) and the frequency of temperature points acquired per second.

Numerical tests are shown in Tab. 2. The LES model was simulated with the parameters mentioned in previous sections. The inlet temperatures, mesh, Smagorinsky constant and turbulence intensity were then varied from these simulations. Temperature means values from the experiments were considered when varying the inlet temperatures.

The differences between the experimental and numerical room temperatures are small enough to be considered equivalent regarding the turbulence. Furthermore, the type of analyses being applied in our work is focused only on the frequency content of the temperature signals, their average values being disregarded. In other words, the time-frequency analysis operator emphasizes how the signal is varying, i.e. wave shapes.

Table 1. Experiments

Tests	Room temp. (°C)	Heated temp. (°C)	Acquisition (Hz)
Test01	19	32	1000
Test02	20	34	1000

Table 2. Numerical tests

Tests	Mesh	Smagorinsky constant	Room temp.(°C)	Heated temp.(°C)	Time step(sec)	Turbulence
LES1	Intermediary	0.07	19	30	0.001	1%
LES2	Intermediary	0.18	19	30	0.001	1%
LES3	Intermediary	0.2	19	30	0.001	1%
LES4	Intermediary	0.1	19	30	0.001	1%
LES5	Coarse	0.1	19	30	0.001	1%
LES6	Fine	0.1	19	30	0.001	1%
LES7	Intermediary	0.07	20	32	0.001	0.5%
LES8	Intermediary	0.18	20	32	0.001	0.5%
LES9	Intermediary	0.2	20	32	0.001	0.5%
LES10	Intermediary	0.1	20	32	0.001	0.5%
LES11	Coarse	0.1	20	32	0.001	0.5%
LES12	Fine	0.1	20	32	0.001	0.5%

The numerical results analyzed by time-frequency diagram have oscillations larger than frequencies of corresponding experiments. These oscillations were up to 20 Hz depending on numerical simulation and thermocouple considered. In case of experiments frequencies of up to 0.5 Hz were observed. The experimental set up is not capable to capture every oscillation of frequency because the time response of thermocouples is 2 seconds approximately. Consequently high frequencies are filtered by the thermocouples. In order to compare the data in time-frequency diagram were considered frequencies only up to 0.5 Hz.

At first, the experimental result test02 produced better results with the simulations LES1, LES2, LES3 and LES4 varying Smagorinsky constant and fixing the same time step, inlet temperatures, mesh and the turbulence intensity at 1%. This comparison is because vortices occur in different thermocouples even when comparing two different experiments (see Figures 3 and 7). Because of this, the objective of this work is to analyze the existence and the shape of turbulent structures.

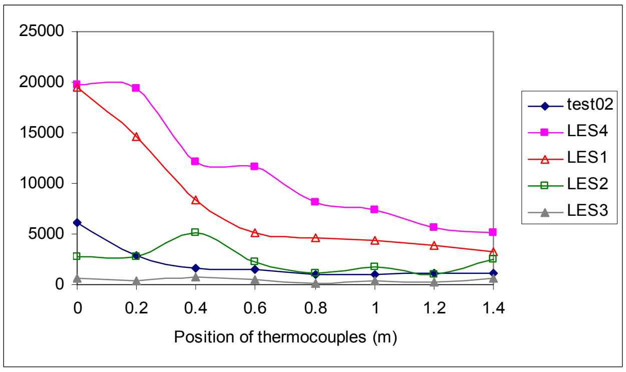

Figure 2: Energy $(°C\ s)^2$ (eq. 18)

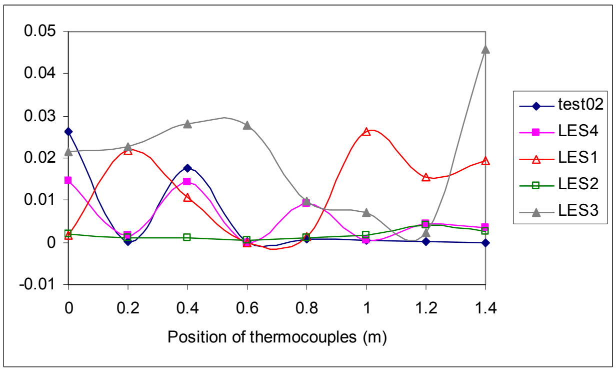

Figure 3: Time-frequency covariance (eq. 26)

According to Fig. 2, the energy is higher at the entrance of the flow indicating an unstable system. It is known that turbulence development needs energy. Furthermore, large vortices need more energy to keep itself and this can be seen at first thermocouples. The best results from numerical simulations were presented by LES2 and LES3, but LES1 and LES4 too represents although its have higher energy. The high energy is probably associated higher amplitudes indicated by numerical simulations signal. According to these energy plots is proved the shape of turbulent structures with large vortices.

As we can see in Fig. 3 about time-frequency covariance, the best result was LES4. Moreover LES2 and LES3 were discarded when compared with test02 because it does not represent the experiment. LES1 simulation present a divergence at thermocouple 6 and from this point on the covariance is higher than LES4 and test02. Moreover LES1 presented a difference in the position of transition thermocouple, but it too represents the experiment. The covariance is high at the beginning when large vortices pass in the flow. The covariance reaches the maximum value in thermocouples 1 and 3, i.e, in these positions we have the recirculation and the formation of small vortices from thermocouple 3 on, representing a more stable flow regime. In other words, the flows transitions are characterized by high time-frequency covariance values when compared with established flow values. This demonstrates the existence of theses vortices and the difference that can occur is only about the transition position. These differences happen as vortices and recirculation pass in the flow. Figure 7 illustrates this difference in results of the time-frequency covariance of test01.

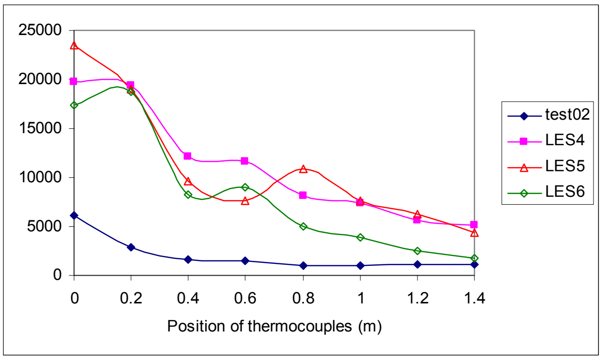

Figure 4: Energy (°C s)^2 (eq. 18)

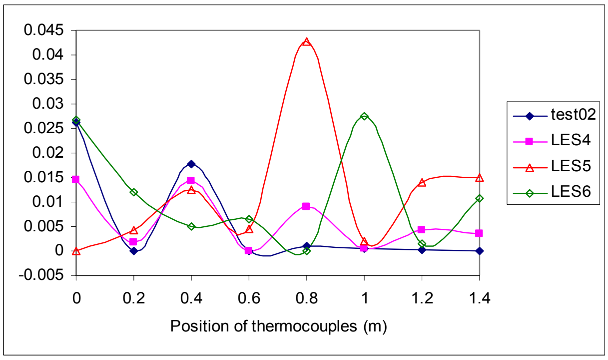

Figure 5: Time-frequency covariance (eq. 26)

Regarding mesh resolution, the experimental result test02 were compared with the simulations LES4, LES5, LES6, fixing the same time step, inlet temperatures, Smagorinsky constant at 0.1 and the turbulence intensity at 1%.

In Figure 4, although simulations have higher energies than test02, they present the same behavior as shown in Fig. 2. The emphasis is in LES6. These high-energies are caused by higher amplitudes from simulations signals when compared with the experiment. Again the shape of turbulent structures with large vortices is proved. According Figure 5 about time-frequency covariance, LES4 simulation was the best representation of the experiment. LES5 and LES6 simulations present a divergence at thermocouples 5 and 6, respectively, but LES5 and LES6 too represents the experiment. This comparison proves the existence of flow transitions with the passage of large vortices.

Regarding turbulence intensity at 0.5%, the experimental result test01 produced better results with the simulations LES7, LES8, LES9 and LES10 varying Smagorinsky constant and fixing the same time step, inlet temperatures and mesh. This comparison is because vortices occur in different thermocouples even when comparing two different experiments.

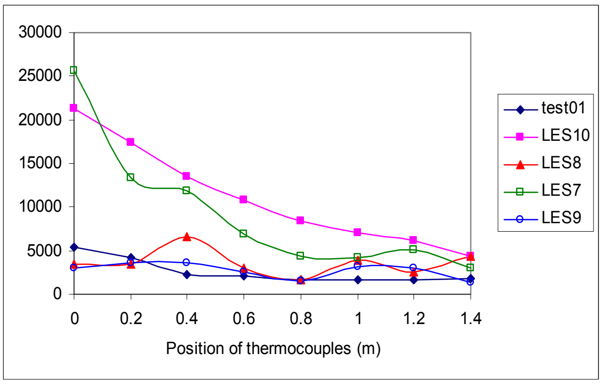

Figure 6: Energy (°C s)^2 (eq. 18)

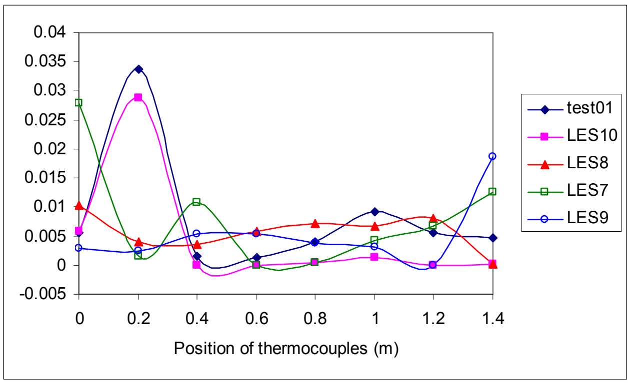

Figure 7: Time-frequency covariance (eq. 26)

LES8 and LES9 do not present good results in time-frequency covariance when compared with test01 as shown in Fig. 7. The best results numerical simulations were LES7 and LES10, although both simulations have higher energies than test01 – see Fig. 6. They present the same behavior as shown in Figures 2 and 4 about energy. In Figure 7, LES7 presented a difference in the position of transition thermocouple and LES10 presented a better representation mainly for the last thermocouples when compared with LES7. Again it confirms the existence of flow regime transitions with the passage of large vortices.

Considering mesh resolution, test01 is compared with LES10, LES11 and LES12, fixing the same time step, inlet temperatures, Smagorinsky constant at 0.1 and turbulence intensity at 0.5%. Despite a small difference between theses numerical simulations LES12 better represents test01, even showing higher energies – see Fig. 8. It is shown in Fig. 9 about time-frequency covariance LES11 and LES12 do not present good results when compared with test01. LES10 presented a better representation mainly for the last thermocouples. Again it confirms the passage of large vortices. Although LES10 produced best results when compared with LES4, we cannot say that experiments have 0.5% of turbulence intensity.

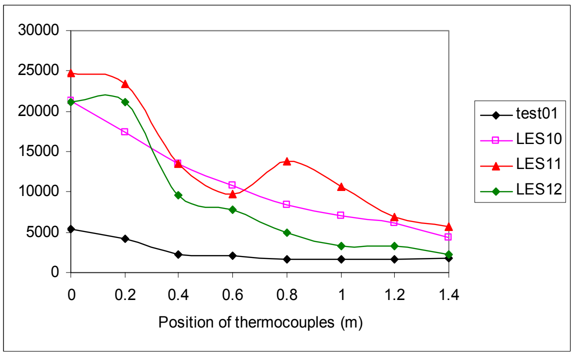

Figure 8: Energy (°C s)^2 (eq. 18)

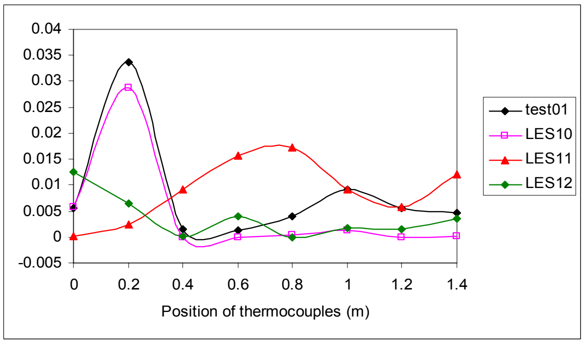

Figure 9: Time-frequency covariance (eq. 26)

The joint time-frequency distribution of thermocouple 1 from LES6 is depicted in Fig. 10 and it indicates the signal unstationarity. Section of the flow with the stream lines of the temperature distribution from LES10 are plotted in Fig. 11. We can also verify the complex structures of recirculation.

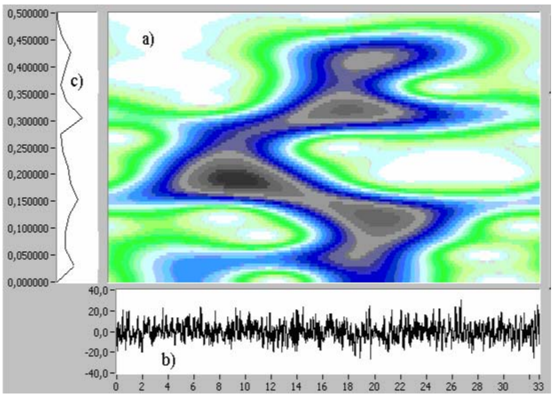

Figure 10: a) Time-frequency distribution;
b) The temperature signal (°C versus time in seconds);
c) The signal spectrum (frequency in Hz is vertical).

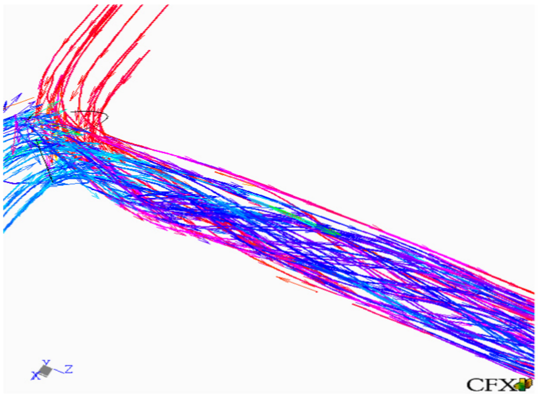

Figure 11: Section with the stream lines of the temperature distribution (K) from LES10.

6. CONCLUSIONS

A comparison between experimental results obtained from a tee air mixer and numerical simulations obtained from a Large Edge Simulation is presented in this work. The software CFX® was used for numerical simulations. The caparison was done by joint time-frequency analyses. Theses comparisons tested the influence of Smagorinsky constant and mesh refining of LES numerical methods relating to the ability of represent the experiment. The emphasis in this representation was about large scale turbulence phenomenon in order to characterize the existence and shape of theses structures.

Several numerical tests indicated that these model presented higher frequencies than experimental measures. Experimental tests were done in an air tee mixer specified in Fig. 1. The analysis was done up to 0.5 Hz to be consistent with experimental data. Future works must include numerical high frequencies investigations of the experiments, and consequently the observation of the smallest vortices, improving the acquisition of the experimental data with an anemometer system. Also a beehive should be put soon after the fans, obtaining a more homogeneous flow in the two entrances and physically more coherent with the numerical flow.

The existence and shape of vortices were identified through time-frequency analysis once the exact position where they occur is not possible to be determined. The energy plot evidenced the large vortices. In this case the energy was high at the entrance and decreased as the flow reached the outlet. Time-frequency covariance plots showed the existence once they indicate oscillations and consequently the unstationarity and flow regime transitions as the vortices pass in the flow.

Numerical simulations with conditions near to experimental ones were performed. In these simulations were varied: inlet temperature, mesh resolution, Smagorinsky constant and turbulence intensity. In theses cases were always considered the same numerical method (LES) and same time step. Theses simulations also confirmed the existence and the shape of large vortices turbulent structures and its results were near to the experiments.

For the numerical and experimental tested conditions, the simulations that produced better results, mainly in the graphs of time-frequency covariance were simulations (LES1, LES4, LES7 and LES10) which possesses temperatures of entrance very close, same mesh resolution, varying both the Smagorinsky constant and the turbulence intensity. Once turbulence intensity has no physical meaning in LES model, we cannot certify that experiments have 0.5% of turbulence intensity. The mesh refinement (LES6 and LES12) was important mainly in the graphs of energy and it also represents the experiments in the graphs of time-frequency covariance.

Future works must include numerical low frequencies investigations searching for better results when comparing with the experiments. These works also must verify time step changes, total time increases, further tests of turbulence intensity, numerical methods changes, comparing LES and DES, and further tests of mesh refining.

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