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Assessment of Turbulence Characteristics for the Baghdad city

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Abstract:

In this paper, the turbulent kinetic energy (TKE) value was estimated and calculated as an important indicator of turbulence. The directional distribution of the TKE value was observed for different directions of the location. The relationship between variables of different turbulent characteristics (e.g. Turbulence for horizontal wind velocity, Horizontal Momentum Flux MF, air temperature and density) and kinetic energy induced by horizontal wind turbulence, has been tested. And finding a mathematical formula describing this relationship.

The data recording process in the city of Baghdad continued for a whole month from 1/7/2016 to 31/7/2016 using fast-response wind velocity measuring instruments. The records included the three components of wind velocity (u, v, w) and temperature and sound speed, recorded observations of the times 3: 00.6: 00.9: 00.12: According to local time Baghdad. Also, air pressure was recorded on hourly basis for the same day through the automatic weather station (Davis vantage pro 2).

Keywords: Atmospheric Boundary layer, Turbulence, Turbulent kinetic energy, Momentum Flux, Turbulence intensity

Introduction:

Most of human activities occur in the boundary layer, especially in the surface layer which forms 10% of the planetary boundary layer making it essential to study the properties and the formation of the boundary layer [1].

Estimating horizontal wind speed is important from an engineering perspective, it affects the design of high buildings, takeoff and landing of airplanes, telecommunications, long bridges, pollution and wind energy. Thus, it is very useful to know the behavior of local wind and especially the wind profile structure.

For this reason, meteorological and engineers were interested in studying the properties and formation of air disturbance in this boundary layer, which appears in a form of irregular circular movements called eddy motion. The extension of energy into the deeps of the boundary layer results from inertia of the fluids where large eddy results into smaller whirls until the whole energy is converted into heat [2].

Studying the boundary layer is conducted vertically through studying wind variations, temperature, humidity levels and other factors. The conclusion of this study results in mathematical equations that contributes to the understanding of this layer. The energy that results from wind speed turbulence is called the turbulent kinetic energy (TKE) and it is one of the most important factors in micro meteorology science. TKE is a measure for the turbulence intensity (I) in the boundary layer. It is also used occasionally to measure the tendency of the flow to be disturbed troubled, thus, TKE is also an indication of stability in the boundary layer [3].

In 1986, Globe and Yersel calculated wind speed in one level and neutral weather conditions using logarithmic variation of wind profile of urban areas, then each of the researchers studied the same variations in near-neutral conditions [4]. Later in 1998, King, Roth, Oke and Grimmond studied the nature and effect of roughness on wind motion near surfaces in urban areas using direct wind observation. This study used fast response anemometers to measure wind speed in addition to typical low response anemometers that are used in meteorological stations [5]. Grimmond and Oke conducted another study in 1999 to study the properties of wind motion over urban areas depending on analyzing the shape of the surface below, they concluded a formula to calculate most of the aerodynamic properties of the area [6]. A more recent study by Al-shamary in 2006, studied the properties of the boundary layer in Baghdad during night and day time through the vertical variations of wind velocity and the temperature using radio sound showing that the altitude of the boundary layer is no more than 2000m and that the surface layer is no more than 250m for the same city [1].

In 2010, Carolyn, Janelle and Bunker studied the effect of wind direction and velocity on wind turbulence and shear [7]. Fernando, conducted a study in 2013 to quantify the effect of wind direction on turbines and found that energy losses in a wind farm are high [8].

Many other studies were conducted to estimate and analyze the value of TKE, Valerie-M. Kumer used static LIDAR with Doppler beam swing (DBS) technology in 2016 to analyze, evaluate and quantify TKE. The same study also used data collected from other devices including wind cube and sonic anemometer in an unprecedented pairing and concluded that the thermal load or the shear that results from it leads to forming whirls in the boundary surface layer with similar turbulence properties [9].

1. THEORETICAL PART

The calculation of turbulence using only analytical methods is not possible, for this reason, statistical analysis are employed to find values for turbulence intensity (I) as an indication for turbulence where it is possible to find it for a compound (x) of wind velocity components as follows [3]:

$$I = \frac{\sigma_x}{\bar{x}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1),$$

Where:

σ_x: Is the standard deviation for wind velocity values of any component(u, v, w).

$\bar{x}$: Is the average wind velocity for any component(u, v, w).

It is also possible to calculate the standard deviation for the component (x) using:

$$\sigma_x = \sqrt{\frac{\sum (X_i - \bar{X})^2}{N}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where:

X_i: is the instantaneous value for wind speed of component(X).

$\bar{X}$: is the average wind velocity for component (X).

N: is the number of recordings.

The value of TKE is one of the most important variables in micro meteorology as it indicates the turbulence intensity. It is directly related to the transmission of momentum, temperature and humidity within the boundary layer [3]. Kinetic energy is denoted by (K.E) and is defined by the equation:

$$K.E = \frac{1}{2} * mass * (velocity)^2 \quad \ldots\ldots\ldots\ldots (3)$$

The instantaneous value for kinetic energy per mass is defined by:

$$e = \frac{1}{2}(u'^2 + v'^2 + w'^2) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

However, due to fast variations for the values of *(e)* with time, the average value for them is used to calculate the TKE value *($\bar{e}$)* as follows [3]:

$$\bar{e} = \frac{TKE}{m} = \frac{1}{2}(\overline{u}'^2 + \overline{v}'^2 + \overline{w}'^2) \text{ ……………………… } (5)$$

The momentum flux (MF) is defined as the momentum transmitted during a specific time through a specific area measured using common units, the momentum is a mass moving at a specific velocity and is measured by (N/m^2), MF can be calculated as follows [2]:

$$MF = \overline{\grave{u}\grave{w}} \text{ ………………………………………………………………. } (6)$$

Where:

$\grave{u}$: is the turbulence in wind velocity towards the axis(x).

$\grave{w}$: is the turbulence in wind velocity towards the axis(z).

It is sometimes called the vertical velocity. The air density can be calculated using the speed of sound as follows [10]:

$$SS = \sqrt{\frac{r \times P}{\rho}} \text{ ……………………… } (7)$$

Where SS is the speed of sound in air, P is the pressure of surrounding air, and r is the heat capacity under a static pressure and it is considered 1.4 [10].

2. MATERIALS, DEVICES AND METHOD

- **Instrument:**

  In this research, a fast response anemometer *(Ultrasonic anemometer, Wind master pro UMG07914-1189-PK-021)* was used. This device is able to measure the velocity for each of the three wind components (u, v, w) per second, it can also measure and record the speed of sound in air and the air temperature at the same time. One of the advantages of using this device is that it provides an enormous amount of data in a relatively short period of time.

- **location:**

  The longitude of Baghdad is 44.5 east and the latitude is 33.14 north, the Mustansiriya district is one f the north eastern areas of Baghdad and is considered an urban area. Devices were installed at an altitude of (18m). The work area is surrounded mostly by two floors or three floors buildings.

- **observation:**

The data was recorded over two steps, the first step included reading recordings from the fast response anemometer at the times: 3:00, 6:00, 9:00 and 12:00 for the period between 01/7/2016 – 31/07/2016. The second step included performing hourly readings for 24 hours on 04/05/2016 and it included the three components of wind velocity (u, v, w) and temperature, in addition to the speed of sound that is used to measure air density. As it is commonly known, the time difference between two recordings using fast response anemometers is one second. The air pressure is recorded on hourly basis for the same day through the automatic weather station (davis vantage pro 2).

3. RESULTS AND DISCUSSION:

a) Turbulent Kinetic Energy

The maximum value of TKE reached (4.9631475 m^2/s^2) and that was on the 24/07/2016 at 9:00 AM. The minimum value was recorded at 3:00 AM on th 06/07/2016 was (0.0670331 m^2/s^2) as shown in Fig 1 which shows the daily change of TKE with the recorded hours.

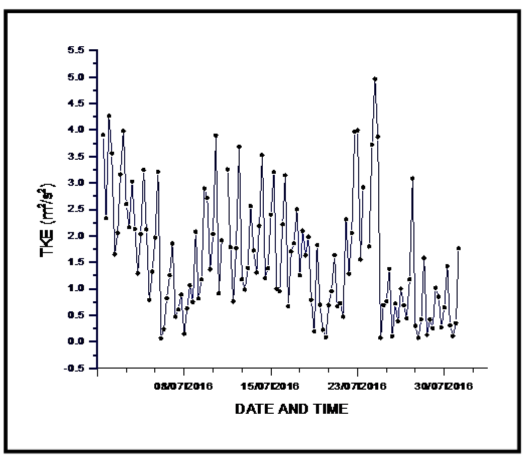

Fig 1. The daily variations of TKE during July 2016

The effect of temperature on TKE is clear as higher temperatures lead to lower air density in the surface layer and decrease the value of TKE. Fig 2 shows the inversely proportional relationship between temperature and TKE with a Correlation coefficient R= - 0.51965 which is an acceptable value, the mathematical equation for this relationship can be stated as follows:

$$TKE = 4.60111 + -0.0746 \times T \quad \text{..................(8)}$$

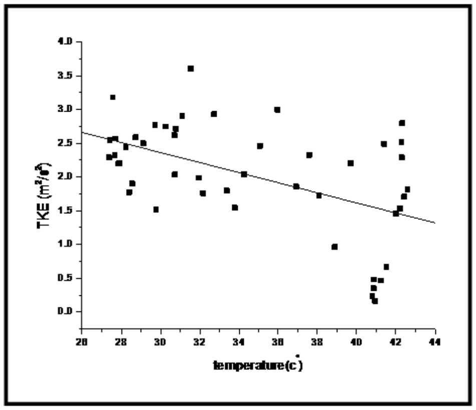

Fig 2. The relationship between temperature and TKE

R= -0.51965

Y = 4.60111+ -0.0746* X

Since TKE is calculated per a unit of mass as shown in equation 4 and 5, the relationship between air density and TKE is proportional, an increase in air density results in an increase in the TKE value as shown in Fig 3. This figure draws the relationship between air density and KTE with a Correlation coefficient R= 0.53 which is also acceptable, the mathematical formulation to describe that is:

$$TKE = -0.05052 + 0.03926 \times \text{Density} \ldots\ldots\ldots\ldots\ldots\ldots (9)$$

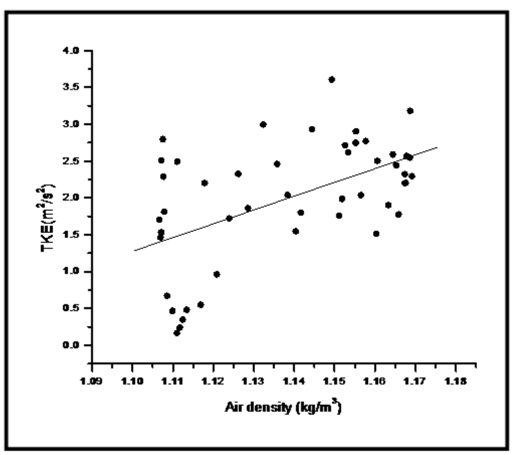

Fig 3. The relationship between air density and TKE

R = 0.53

Y = -0.05052 + 0.03926 * X

The stretching and torsion in air discharge (distortion) during movement in addition to turbulence results in TKE, the main source for this turbulence is the components of wind and the temperature variation with altitude, in the case of stable labs rate, the wind shear and the instability contribute to generating the turbulence [11].

Fig 4 shows the directional distribution of TKE, while Fig 5 shows a satellite photo of the area where data was recorded. Most of TKE is concentrated in directions with high density of surface roughness materials, these cause a high wind shear compared to other directions and the maximum value recorded in the direction between 30 and 60 degrees.

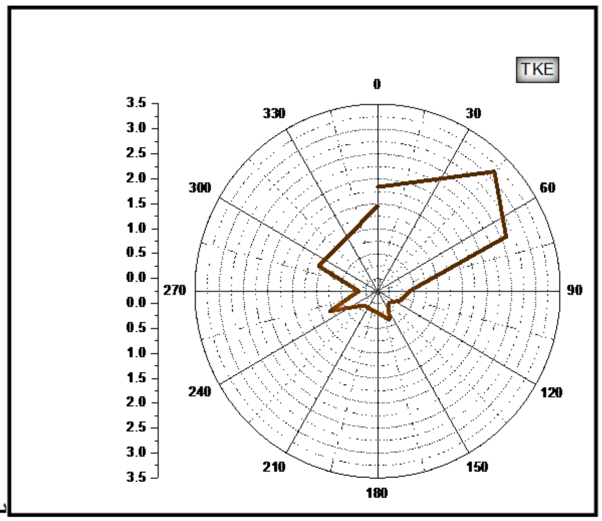

Fig 4. The directional distribution of TKE

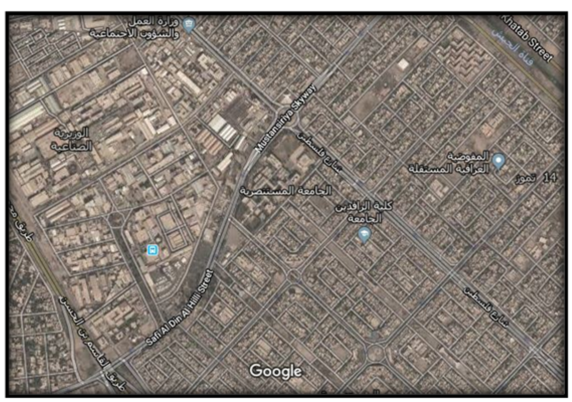

Fig 5. Area where data was recorded

b) Turbulence for horizontal wind velocity

The variation in turbulence intensity of wind velocity in the direction of the horizontal component (u) within 24 hours shows that the highest value for wind velocity turbulence intensity is 0.8004 at 07:30. The minimum value on the other hand was -0.9902 at 23:00 Baghdad local time as shown in Fig 6.

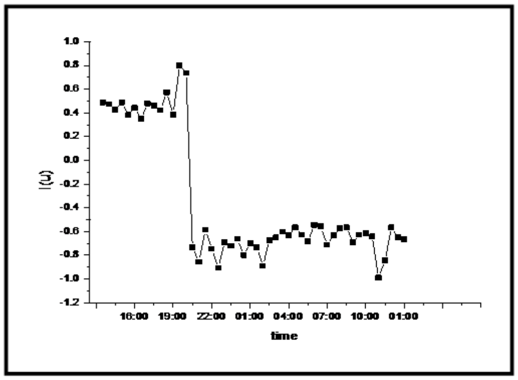

Fig 6. The variation of horizontal wind component velocity (u) turbulence intensity with time

The variation of horizontal wind velocity turbulence intensity in the horizontal component (v) within 24 hours shows that the maximum value of turbulence intensity (I_V) is 1.9186 at 07:30 and the minimum value is -2.6139 at 05:00 Baghdad local time, as shown in Fig 6.

With regards to the vertical component (w), the maximum variation of turbulence intensity for wind velocity was 27.24 at 04:30. The minimum value was 2.59 at 23:00 Baghdad local time as shown in Fig 7.

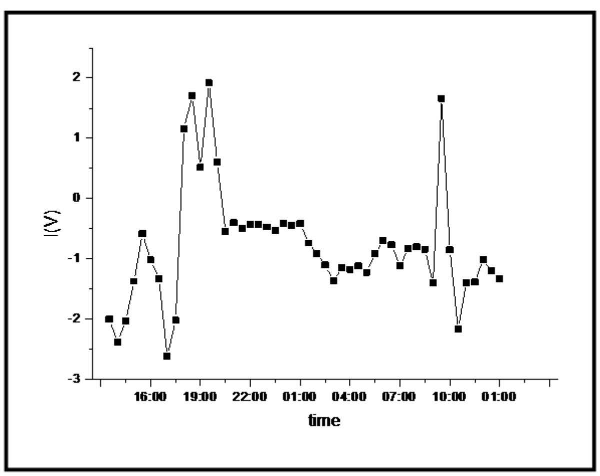

Fig 6. The variation of turbulence intensity with time in wind horizontal component (v).

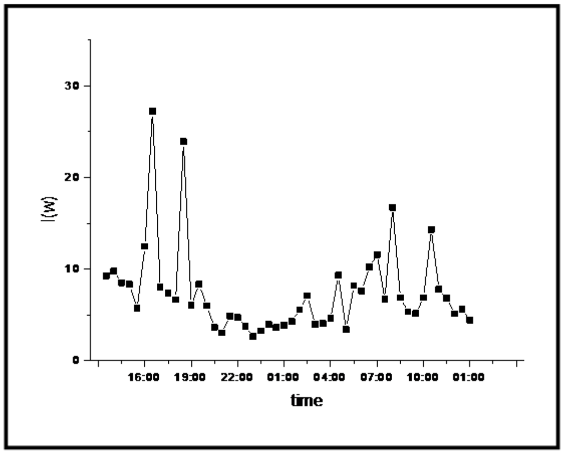

Fig 7. The variation of turbulence intensity with time in vertical wind component (w).

Results show that temperature has a clear effect on the turbulence intensity in the direction of the component (u) as shown in Fig 8, which shows that the turbulence intensity increases logarithmically with increased heat. Temperature leads to increase buoyancy Which activates the vertical motion which is Causing obstruction of horizontal wind velocity and decreasing the average velocity in the direction of (u) component. The relationship between the average horizontal wind velocity and the turbulence intensity is inversely proportional (a decrease in the average horizontal wind velocity leads to an increase in wind velocity turbulence intensity) [12].

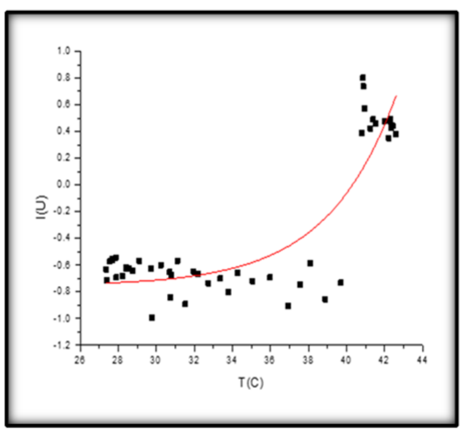

Fig 8. The relationship between temperature and turbulence in wind velocity in the direction of (u) component

After this explanation, it is possible to understand the relationship between TKE and turbulence intensity as shown in Fig 9 and Fig 10. Increasing temperature leads to a decrease in air density and a decrease in TKE as previously shown in Fig 3. Thus, TKE is inversely proportional with the wind velocity turbulence intensity in the direction of (u) and (v) components.

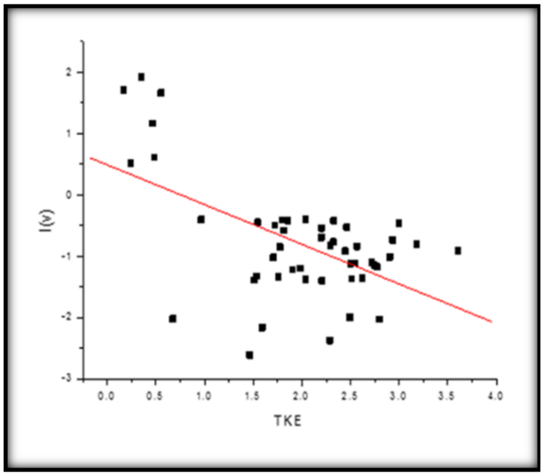

Fig 9. Relationship between TKE and turbulence in the direction of (v) component

R= - 0.55 $I_v = 0.48785 + -0.64739 \times TKE$

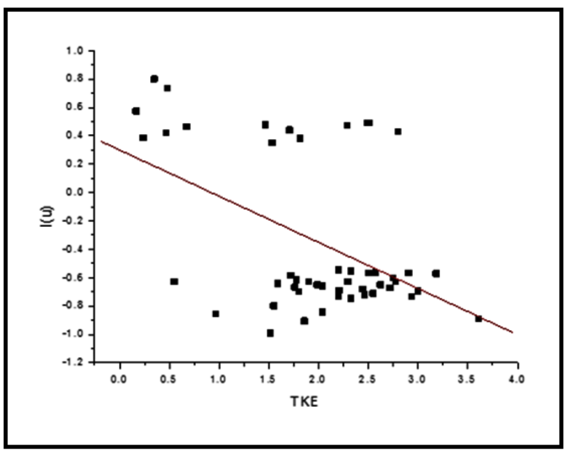

Fig 10. Relationship between TKE and turbulence in the direction of (u) component

R= - 0.5

$$I_U = 0.2995 + -0.2357 \times TKE$$

c) Horizontal Momentum Flux MF

The value of MF was estimated and calculated for a full month on a daily basis for the times shown in the observation section. Fig 11 shows the variations in horizontal MF for wind where the maximam value was on 05/07/2016 at 12:00 Baghdad local time. The minimam value was -0.08487 and it was recorded on 20/07/2016 at 9:00 Baghdad local time.

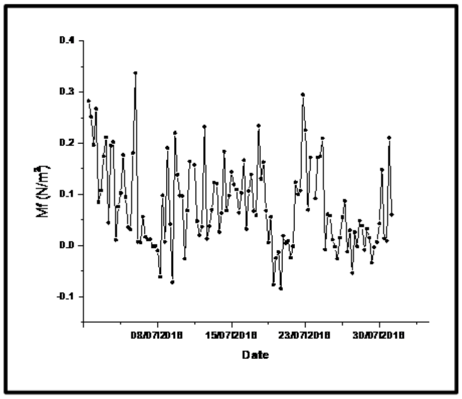

Fig 11. Variations in horizontal MF for wind with time

An inversely exponential relationship was found between MF and horizontal wind turbulence intensity I_U in the direction of (u) component. The value of determiation coefficient for this relationship is R^2=0.66 as shown in Fig 12. The mathematical equation that describes this can be formulated as follows:

$I_U = -1.0629 + 0.874 * e^{(-MF/0.1934)}$....................(10)

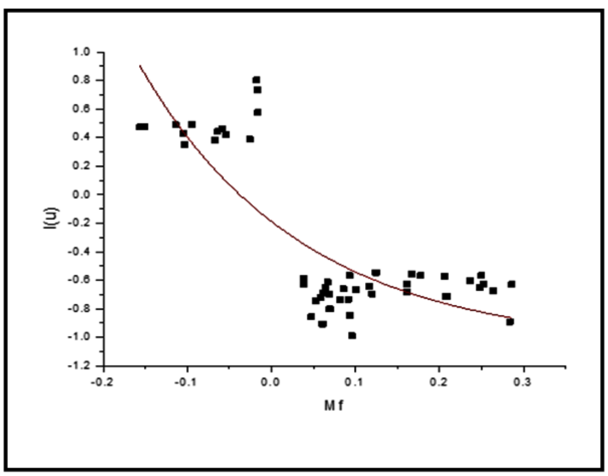

Fig 12. Relationship between MF and horizontal wind velocity turbulence I_U in the direction of (u) component

It seems that there is a complicated relationship between MF and wind velocity turbulence intensity that depends also on temperature and thus air density, which is proportional to horizontal MF and inversly proportional to wind turbulence intensity turbulence in the direction of (u) in a Polynomial equationas shown in Fig 13 and Fig 14. It is clear that the reaction of MF and wind velocity turbulence intensity with air density are opposites which justifies the inverse relationship between tubulence intensity and MF.

The horizontal MF had no effect on turbulence intensity in the direction of (v) and (w) components.

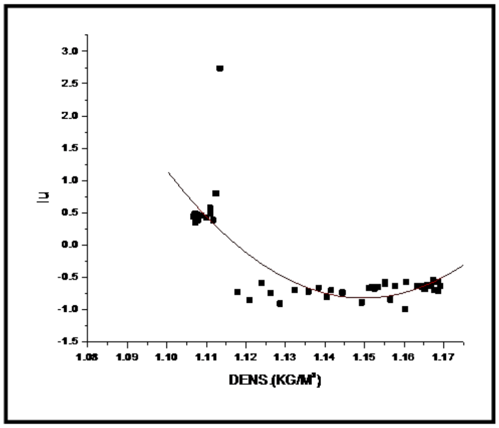

Fig 13. Relationship between air density and horizontal wind turbulence intensity turbulence in the direction of (u) component

R^2= 0.6165

Iu = 1054.05687 + (-1834.97987) × DENS. + 797.9946 × X^2

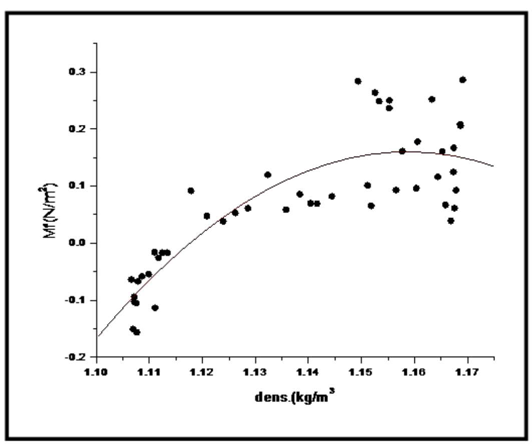

Fig 14. Relationship between air density and horizontal MF

R^2 = 0.7267

Mf = -127.4769 + 220.32056×DENS. + -95.07658×X^2

4. CONCLUSIONS:

At a first sight, it seems that TKE is significantly affected by turbulence intensity resulting from wind shear. However, results show that the mass of moving air plays a very important role in producing TKE where air density is proportional to TKE. Also, air density is proportional to horizontal MF in a polinomial equation that shows the dependency of MF on the mass of moving air as well.

With regards to I_U, the turbulence of wind velocity in the direction of (u), it was found that higher temperature leads to more turbulence which is also inversly proportional to TKE and MF. The same applies to I_V the turbulence intensity of wind velocity in the direction of (v).

The horizontal MF had no effect on turbulence in the direction of (v) and (w).

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