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# Determination of Heat and Momentum Fluxes over Baghdad

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## Abstract

The heat and momentum fluxes have been determined at Al-Mustansiriyah University, Baghdad, Iraq, by using eddy correlation method. It is one of the methods which determine heat and momentum fluxes, it is considered direct and accurate. This method depends on high response instruments like Ultrasonic Anemometer (model: 1590- PK- 020). Observation period is about 53 days for 24 hours in months June, July and August (summer season) from 15/06/2016 to 06//08/2016 and the observations included wind speed and temperature every second. Huge data treated by MATLAB program to calculate heat and momentum fluxes (H and τ). The maximum value of H equals 127.6 Wm-2 in 10:30 at 26/07/2016 and minimum value equals -58.9 Wm-2 in 07:30 at 29/06/2016, as well, the maximum value of τ equals 0.134535 Nm-2 in 15:00 at 03/08/2016 and minimum value equals -0.4649 Nm-2 in 03:00 at 01/07/2016 (negative sign refer also to change in direction flow) . It is found that there is an inverse relationship between H and τ. Fractional drag by wind speed, also deal where Maximum frequency of friction velocity is at unstable conditions.

**Keywords**: Momentum flux, Heat flux, Obukhov length, Atmospheric Stability.

## الخلاصة

تم تحديد فيض الحرارة والزخم في الجامعة المستنصرية، بغداد، العراق، بأستخدام طريقة ارتباط الدوامة وهي واحدة من الطرق التي تحدد او تحسب فيض الحرارة والزخم وتعتبر طريقة مباشرة ودقيقة. هذه الطريقة تعتمد على اجهزة ذات استجابة عالية مثل جهاز Ultrasonic (نموذج : ١٥٩٠- PK- 020) والذي استخدم في الدراسة. مدة الرصد كانت ٥٣ يوم لمدة ٢٤ ساعة خلال الاشهر حزيران وتموز وآب من ٢٠١٦/٠٦/١٥ الى ٢٠١٦/٠٨//٠٦ وتتضمن الرصدات سرعة الرياح ودرجة الحرارة كل ثانية. كذلك تم استخدام برنامج MATLAB لمعالجة البيانات الكبيرة ومن ثم حساب فيض الحرارة والزخم ((H and τ حيث كانت اعلى قيمة لـ H تساوي ١٢٧,٦ Wm-2 عند الساعة ١٠:٣٠ في يوم ٢٠١٦/٠٧/٢٦ واقل قيمة تساوي -٥٨,٩ Wm-2 عند الساعة ٠٧:٣٠ في يوم ٢٠١٦/٠٦/٢٩ كذلك كانت اعلى قيمة لـ τ تساوي ٠,١٣٤٥٣٥ Nm-2 عند الساعة ١٥:٠٠ في يوم ٢٠١٦/٠٨/٠٣ واقل قيمة تساوي -٠,٤٦٤٩ Nm-2 عند الساعة ٠٣:٠٠ في يوم ٢٠١٦/٠٧/٠١ ( الاشارة السالبة تشير الى التغير في اتجاه الحركة ) . وقد وجد هنالك علاقة عكسية بين H و τ . السحب الاحتكاكي بواسطة سرعة الرياح تم تناوله ايضا ، حيث كانت اعلى قيم تكرارية للسرعة الاحتيكاكية عند الظروف الغير مستقرة.

## Introduction

Flux is transfer of a quantity per unit area per unit time. In Boundary layer, it is often concerned with mass, heat, moisture, momentum and pollutant fluxes. Momentum is mass times velocity (kg•m/s), thus, a momentum flux is (kg•m/s)/(m2.s). These units are identical to N/m2, which are the units for stress. Quantities such as heat or momentum rarely measure directly, Instead we measure things like temperature or wind speed. Therefore, for convenience the above fluxes can be redefined in kinematic form by dividing by the density of moist ρ air. In the case of sensible heat flux, we also divide by the specific heat of air [1]. Operation in air pollution models needs deterministic of surface layer parameters such as roughness length, sensible heat flux and surface stress in order to estimate the dispersion of pollutants within the Boundary Layer (BL) [2]. The turbulent momentum (ρu_*^2) and sensible heat (H) fluxes are two of the important parameters necessary to quantify Land-Atmosphere interactions and energy transport processes in the Atmospheric Surface Layer (ASL). On the



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basis of turbulence measurements in the ASL, several methods have been developed to determine these fluxes, including (1) Direct eddy correlation method, (2) Dissipation method and (3) Flux-variance method [3]. Many study done in atmospheric sciences about calculate heat and momentum flux for example, Romi,T.A. (2000) compute sensible heat flux and Monin-Obukhov length, these parameters are used in log-linear profile relationship and power law to make estimates of wind speed and temperature at height 100m above Baghdad city [4]. Zehra Salah (2008) estimate the effect of horizontal and vertical flux concerning PM10 (particle matter at diameter 10um) for period 1951-1980 and for stations Baghdad, Basra, Mosul and Rutba on atmospheric element atmospheric pressure, temperature, relative humidity cloud cover and wind speed. It found that Wind speed have the great effect over the most other elements, specifically in Rutba station [5]. Hussun A. F. (2011) test the effect of sensible heat flux and momentum flux calculated by installing tower over roof of the engineering college building Mustansiriyah university on aerosol channels at particle sizes 25um, 10um, 5um, 1um, 0.5um and 0.3um [6]. Aqeel and Hassun A. F. (2011) used a slow response instrument to measured wind speed and temperature at two levels 20 m ,15 m at a selected hours of the day from 16:00 LT to 20:00 LST throughout a month (April 2006). From these observations, estimation has been done to measure and evaluate an exponential relation between Abu-khov Length and sensible heat flux equation that used under specific condition. In this work maximum abu-khove Length value was (-249.2) and minimum Obkhove Length value was (- 2638.1m), as well. The maximum heat flux value was (19.7w/m2) and the minimum heat flux value was (1.9 w/m2) [7].

***Location***

Al-Mustansiriyah University location (Atmospheric Sciences Building) with 33°22'2.152"N, 44°24'12.912"E and at an elevation of 31.7m above mean sea level was chosen. This location is sited on the east part of Baghdad; it consists mainly of various roughness elements such as low houses with 3m height to tall buildings with more than 30m such as government offices. The study site is surrounded by trees and approximately 80% of buildings.

***Data and Tools***

Data have been obtained from Ultrasonic anemometer device, Model: 1590- PK- 020. It's offering three-axis wind measurement data. This instrument monitors wind speed of 0~50m/s and provides sonic temperature, speed of sound and u, v, and w components outputs at 1Hz. This anemometer constructed from aluminum/carbon fiber its ideal used for understanding turbulent flows, surface energy balance and scalar fluxes. 3D sonic anemometer suited to the measurement of air turbulence around bridges, buildings, wind turbine sites, building ventilation control systems, meteorological and flux measurement sites. The wind master anemometer measures the times taken for an ultrasonic pulse of sound to travel from an upper transducer to the opposite lower transducer, and compares it with the time for a pulse to travel from lower to upper transducer [8], see Figure 1.

**Figure 1**: Ultrasonic anemometer device above the building Al-Mustansiriyah University College of sciences.

This type of device is used in this work to calculate heat and momentum fluxes over Baghdad city; it is installed about 19m height above the ground surface as shown in Figure 1.

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Data logger connected with devise because there is discontinuity in data records specifically at night, we will only depend on the continuous recorded data. Data were gathered in June, July and many days in August month. the continuous observation period is about 53 days from 15/6/2016 to 6/8/2016, the recorded data are in every second for 24 hours and the observations included wind speed and temperature, the observations number in this study are 2541.

Programs such as MATLAB and Origin have been used for analysis and plot of the data.

Figure 2, demonstrates the flowchart of main program. Script M-File in MATLAB program, this program uses input data for the Ultrasonic anemometer device for the components of u, v, w, T and time every second. This model computes the following output data:

- Average Horizontal wind component at (x) direction at 30minte (u- 30)
- Average Horizontal wind component at (y) direction at 30minte (v- 30)
- Average Horizontal wind component at (z) direction at 30minte (w- 30)
- Average temperature component at 30minte (T- 30)
- Average Momentum flux component at 30minte (u'w')
- Average Heat Flux component at 30 minte (w'T')
- Average Momentum flux component at 30minte v- flux [ (u'v') ]
- Average Momentum flux component at 30minte, v- momentum1, v- momentum2 [v'T', v'w']
- Average Shear stress at 30 minte, Tau, [ $\rho\, u_*^2$]
- Average Sensible heat flux at 30minte

The input data processed by separated program, titled subroutine mean-data. Components u-30 …T-30 mean, observation average for these components at 30min, the observation component resulted can be substituted in equations of momentum flux and sensible heat flux.

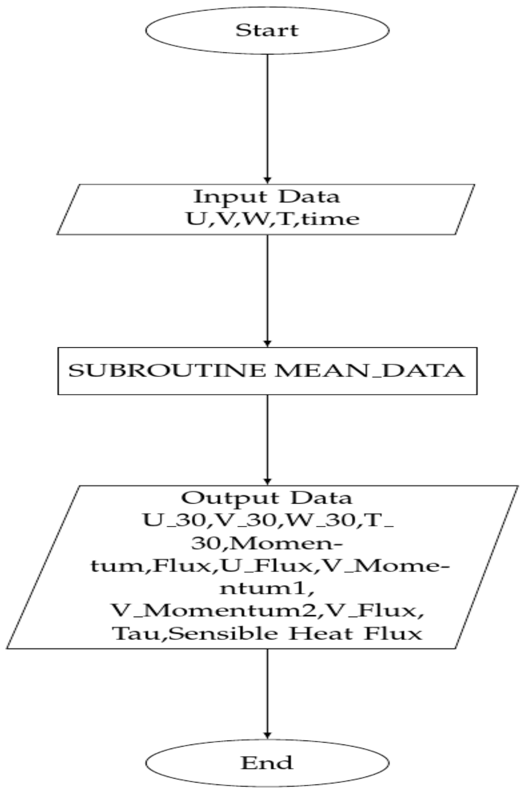


**Figure 2**: Demonstrates the flowchart of main program used to treat sonic data.

## Methodology and statistical methods

One statistical measure of the dispersion of data about the mean is the variance $\sigma^2$, defined by:

$$\sigma_A^2 = \frac{1}{N}\sum_{i=1}^{N-1}(A_i - \bar{A})^2 \quad (1)$$

Where $A$ is any variable, recall that the turbulent part (the perturbation or gust part) of a turbulent variable is given by $A' = A_i - \bar{A}$. Substituting this into the variance (Equation 1) gives:

$$\sigma_A^2 = \frac{1}{N}\sum_{i=0}^{N-1} A'^2 = \overline{A'^2} \quad (2)$$

The standard deviation is defined as the square root of the variance [9]:

$$\sigma_A = \left(\overline{A'^2}\right)^{1/2} \quad (3)$$



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In statistics, the covariance between two variables is defined as [10]:

$$covar(A,B) = \frac{1}{N}\sum_{i=0}^{N-1}(A_i - \bar{A})(B_i - \bar{B})$$

$$covar(A,B) = \frac{1}{N}\sum_{i=0}^{N-1}A'B' = \overline{A'B'} \quad (4)$$

The covariance indicates the degree of common relationship between the two variables, A and B. For example, let $A$ represent air temperature T, and let $B$ be the vertical velocity w. On a hot summer day over land, one might expect the warmer than average air to rise (positive T' and positive w'), and the cooler than average air to sink (negative T' and negative w'). Thus, the product $w'T'$ will be positive on the average, indicating that w and T vary together. The covariance $\overline{w'T'}$ is indeed found to be positive throughout the bottom 80% of the convective mixed layer [11].

***Eddy Correlation Method (ECM)***

The eddy correlation method considered to be the most accurate method, measures the fluxes directly by measuring the covariance between the turbulent flow variables. However, routine application of this method in field experiments requires (1) high sampling rates (e.g., 1–20 Hz), (2) precise orientation and alignment of sensors, and (3) long sampling duration (e.g., 30 min) to obtain stable statistics [3].

Thus it depends on fast response turbulence instrumentation, where if all fluctuations of velocity and temperature are senses and recorded, one can determine their covariance simply by averaging the fluctuations over any desired averaging time. The vertical fluxes of momentum and heat over a homogeneous surface are given by[12]:

$$\tau = -\rho\overline{u'w'} \quad (5)$$

$$H = \rho c_p\overline{w'T'} \quad (6)$$

Where, $\overline{w'T'}$ is the kinematic heat flux, $\overline{u'w'}$ is kinematic momentum flux, $c_p$ is specific heat of air at constant pressure [12].

Airflow can be seen as horizontal flow of multiple eddies. At the level of single air particle, one eddy moves an air particle up/downwards with speed *w*, with a certain gas concentration *c*, temperature and humidity. The momentum, temperature and moisture fluxes can be determined by measuring the movement of particles and their characteristics. From these measured characteristics, the change of the temperature and moisture can be determined. Together with the movement of the particles, the net of flux can be determined as the sum of upward and downward stream of particles. The general principle is explained and can be used for the Eddy Covariance Method to calculate the Obukhov length ($L$) by measuring the parameters according to Table 1 [13]. Momentum and temperature fluxes are calculated as a covariance of fluctuations of vertical wind speed and fluctuations in the other measured characteristics. Measurements of the wind speed in different directions and temperature are used in the Eddy Covariance Method to derive the Obukhov length ($L$).

**Table 1**: Required parameters for the Eddy Covariance Method.

| Parameter | Measurement frequency |
|---|---|
| *u* horizontal wind speed (m/s)<br>*v* horizontal wind speed perpendicular to *u* (m/s)<br>*w* vertical wind speed (m/s)<br>*T* absolute temperature (°C) | High frequency (1-20 Hz) |
| *RH* relative humidity (%)<br>*p* pressure (pa) | Low frequency (1/600 Hz) |

The wind speed and temperature are measured using a high frequency sonic anemometer. The high frequency measurements are used to determine the fluctuations in time of the temperature and wind speed in the vertical and the horizontal direction by coupling the fluctuations of the temperature and the horizontal wind speed with the vertical wind speed measurements [13]. Overall, Eddy Correlation Method is often considered to be the most accurate method and it is normally used as a reference to other methods to calculate heat and momentum fluxes [14].

***Friction Velocity***

Using the covariance of the fluctuations of the horizontal wind speed with respect to the vertical wind speed, the friction velocity can be computed as [15]:

$$u_* = \sqrt[4]{(\overline{u'w'})^2 + (\overline{v'w'})^2} \quad (7)$$

By rotating the coordinate system in the direction of the surface stress, a simpler version of equation (7) can be derived for $u_*$ :

$$u_* = \sqrt{\left|-\overline{u'w'}\right|} \quad (8)$$

It has to be taken into account that the measurement frequency determines the perceptibility of turbulent flux carrying eddies [16] [17]. The smallest eddies are determined with the highest frequency and largest eddies with the lowest measurement frequency. In order to determine the fluxes, an averaging period is selected (between 10 and 60 minutes). The length of the averaging period is a compromise between perception of the eddy with the highest contribution of momentum and heat fluxes and the requirement of stationary conditions.

***Displacement Length***

Some roughness elements such as building and trees align closely forming homogeneous obstacle that obstructs the horizontal wind movement, rising up the level where wind speed equals zero. The height of this level is called Displacement Length ($Z_d$), which can be calculated by the formula of Bottema 1995 [18]:

$$Z_d = \left(\frac{\sum A_{rb} + \sum(1-p)A_{rt}}{A_T}\right)^{0.6} * Z_H \quad (9)$$

Where:
$A_{rb}$: The area of buildings.
$A_{rt}$: The area of trees.
$A_T$: The total area.
$p$: The porosity of trees = 0.4
$Z_H$: The mean height of the roughness elements.

***Stability by Obukhov Length***

It is one of stability parameters which represent the ratio of the consumption of turbulence by buoyancy force to the production of turbulence by wind shear. Table 2, shows Qualitative interpretation of atmospheric stability classification according to Obukhov length ($z/L$) which can be calculated by [19]:

$$L = -\frac{\rho c_p T u_*^3}{kgH} \quad (10)$$

Where:
$\rho$: Air density = 1.2 kg/m$^3$.
$c_p$: Specific heat of air at constant pressure = 1004 J.kg$^{-1}$.K$^{-1}$.
$T$: Average temperature.
$u_*$: Friction velocity.
$H$: Sensible heat flux.
$k$: Von Karman constant = 0.4
$g$: Acceleration of gravity.

In the surface layer, both mechanical and thermal forcing influence the turbulence and the variation of the mean variables, a rational method must be found to superpose the effects of these two types of forcing. This was first accomplished by Monin and Obukhov (1954) through their similarity theory [20]. They introduced two scaling parameters, essentially independent of height in the surface layer for velocity and length. These are the friction velocity $u_*$ and the length $L$. Suffice it to repeat here that $L$ depends essentially only on heat flux H and $u_*$. It is numerically small and negative (about -10m) on strongly convective days, about -100m on windy days with some solar heating and approaches infinity in purely mechanical turbulence. At night with downward heat flux, $L$ is positive and small in light-wind stable conditions. We can consider the ratio -z/$L$ to represents the relative importance of heat



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convection and mechanical turbulence in the daytime. At night, the ratio z/$L$ describes the relative importance of the suppression of mechanical turbulence by the stratification. The general properties of z/$L$ are summarized by Table 2.

**Table 2**: Qualitative interpretation of z/$L$ [21]

| $z\text{-}z_d/L$ | Word Description |
|---|---|
| Strong negative | Heat convection dominant |
| Negative but small | Mechanical turbulence dominant |
| Zero | Purely mechanical turbulence |
| Slightly positive | Mechanical turbulence slightly damped by temperature stratification |
| Strongly positive | Mechanical turbulence severely reduced by temperature stratification |

## Results and Discussion

### *Calculation of displacement length*

Before calculation of displacement length, we need to know from where wind comes (known as domain wind), thus wind rose is plot to the location through the period of study from mid of June to beginning of August, by using the data from Automatic Weather Station over Atmospheric Sciences Building, see Figure 3. Most horizontal wind speed that is used to calculate flux comes from direction bounded from N-S, thus calculation of $Z_d$ is taken from these directions only.
Displacement length has been calculated by using equation (9), the studied area is divided into several sectors depending on prevailing wind speed directions. The results are shown in Table 3 and the mean value of $Z_d$ for the studied area equals 10.6 meter.

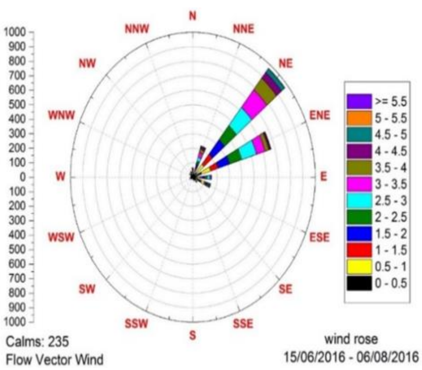
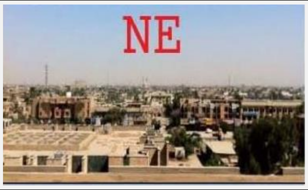


**Figure 3**: Wind rose of study location.

**Table 3**: Shows values of $Z_H$ and $Z_d$ for each sector.

| Sectors | $Z_H$ (m) | $Z_d$ (m) |
|---|---|---|
|   | 10 | 8.12 |
|   | 8.2 | 6.67 |
|   | 8.5 | 6.95 |
|   | 9.5 | 7.86 |
|   | 15 | 13.15 |
|   | 15.8 | 14.29 |
|   | 14.8 | 13.29 |
|   | 13 | 11.05 |
|   | 16 | 14.26 |

### *Calculation of Monin-Obukhov parameter (z/L)*

Obukhov length has been calculated from equation (10) at height of observation is about 19 meter. We take the value of $Z_d$ through calculation of parameter (z/$L$) due to the studied area is considered an urban. The range of z-$z_d$/$L$ between -5981.31 and 47.91, the total observations are 2541. If we take boundary Values of z-$z_d$/$L$ between -10 and 10, taken only because have large rate. It can be noted from that 2495 of observations are in this range (between -10 and 10) about (98.18%). Table 4 shows the frequency of z-$z_d$/$L$. Figure 4 shows the maximum frequency of z-$z_d$/$L$ at bin center of -1.

**Table 4**: Shows frequency of z-$z_d$/$L$ in range from -10 to 10.

| Bin Centers | Frequency | Frequency percentage (%) |
|---|---|---|
| -11 | 2 | 0.078 |
| -9 | 14 | 0.55 |
| -7 | 10 | 0.39 |
| -5 | 22 | 0.86 |
| -3 | 53 | 2.08 |
| -1 | 21 | 82.76 |
| 1 | 278 | 10.94 |
| 3 | 7 | 0.275 |
| 5 | 4 | 0.157 |
| 7 | 1 | 0.039 |
| 9 | 0 | 0 |
| 11 | 1 | 0.039 |

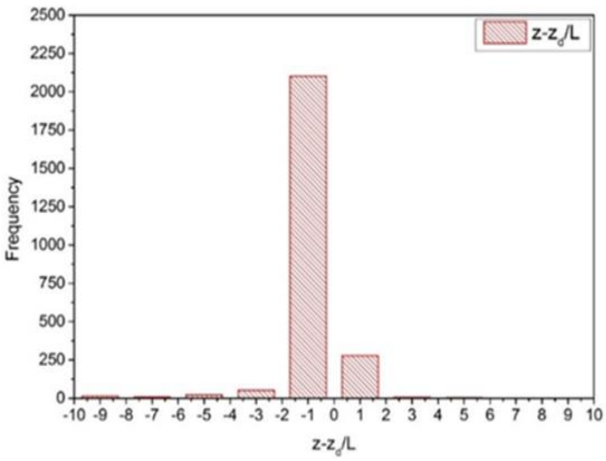



**Figure 4**: Frequency of z-$z_d$/$L$ in range from -10 to 10.

### *Relationship between Friction velocity and Stability*

Friction velocity has been calculated by using equation (8). After calculation of friction velocity, it classified according to atmospheric conditions, where most conditions at unstable about 1746 count (68.7%), neutral conditions are 610 count from all observations about (24%) and stable conditions have small frequency about 185 (7.3%) as shown in Figure 5. This belongs to very hot season conditions (summer) where convective cases are activated. Although friction velocity at neutral conditions have small frequency distribution, but it has large range of Velocity (neutral conditions exist at overcast weather or at weak vertical component of wind speed w), see Figure 5. In unstable conditions friction velocity have large frequency, this belongs to very hot season conditions (summer) where convective cases are activated at daytime.

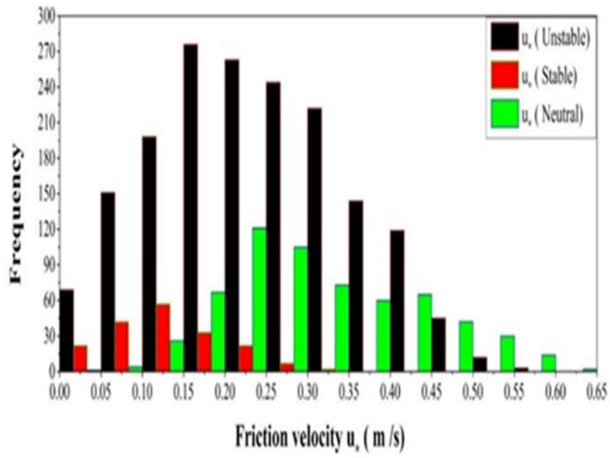



**Figure 5**: Shows frequency variations of friction velocity at stability conditions.

### *Relationship between turbulent components*

After processing the data by using MATLAB and Origin programs several relations between turbulent components such as w'T' and u'w' have been plotted at stability conditions. The correlation coefficients (r) between turbulent components are shown in Table 5. It can be noted that at neutral conditions there are good correlation coefficients between turbulent components. While at unstable conditions, friction velocity is active and thus there are



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slightly good correlation coefficients between turbulent components.

**Table 5**: Shows correlation coefficients (r) between turbulent components at stability conditions.

| Turbulent components | Stability conditions | | |
|---|---|---|---|
| | Stable | Neutral | Unstable |
| w'T' vs v'T' | 0.66 | 0.74 | 0.62 |
| w'T' vs u'T' | -0.66 | 0.81 | 0.48 |
| w'T' vs v'w' | -0.4 | 0.66 | 0.41 |
| w'T' vs u'v' | 0.49 | 0.57 | 0.41 |
| u'w' vs v'T' | 0.41 | 0.51 | 0.46 |
| u'w' vs u'T' | -0.44 | 0.65 | 0.71 |
| u'w' vs v'w' | -0.09 | 0.84 | 0.65 |
| u'w' vs u'v' | 0.51 | 0.67 | 0.64 |
| u'w' vs w'T' | 0.54 | 0.75 | 0.5 |

***Calculation of heat and momentum fluxes***

Heat and momentum fluxes ($H$ and $\tau$) can be calculated from eddy correlation method by using equations (5 and 6). Hourly means variations for hours of days during the observations period have been taken for heat and momentum fluxes as shown in Figure 6. We see that maximum values of $H$ were at noontime, while minimum values of $\tau$ were at noontime. The maximum value of $H$ is 55.89 $Wm^{-2}$ in 11:00, and the minimum value is 1.14 $Wm^{-2}$ in 20:00. The maximum value of $\tau$ is -0.04043 $Nm^{-2}$ in 20:00, and the minimum value is -0.13379 $Nm^{-2}$ in 12:00. Thus, there is an inverse relationship between $H$ and $\tau$.

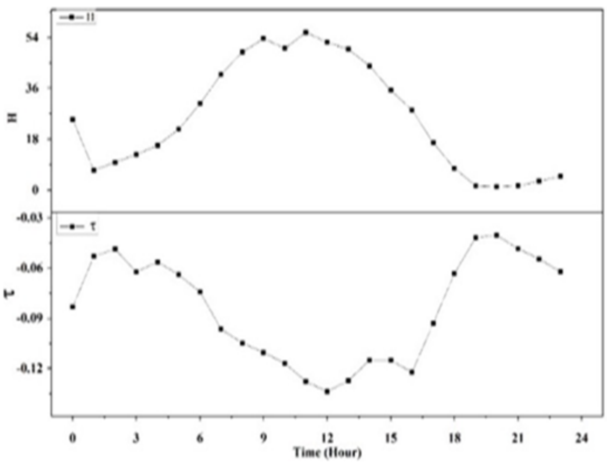


**Figure 6**: Hourly variations of heat and momentum fluxes.

***Heat and momentum fluxes at daytime and nighttime***

The observations number at daytime are 1431, the maximum value of $H$ is 127.6 $Wm^{-2}$ in 10:30 at 26/07/2016, and the minimum value is -58.9 $Wm^{-2}$ in 07:30 at 29/06/2016. While, the maximum value of $\tau$ is 0.1345 $Nm^{-2}$ in 15:00 at 03/08/2016, and the minimum value is -0.43891 $Nm^{-2}$ in 11:30 at 22/07/2016. As shown in Figure 7.

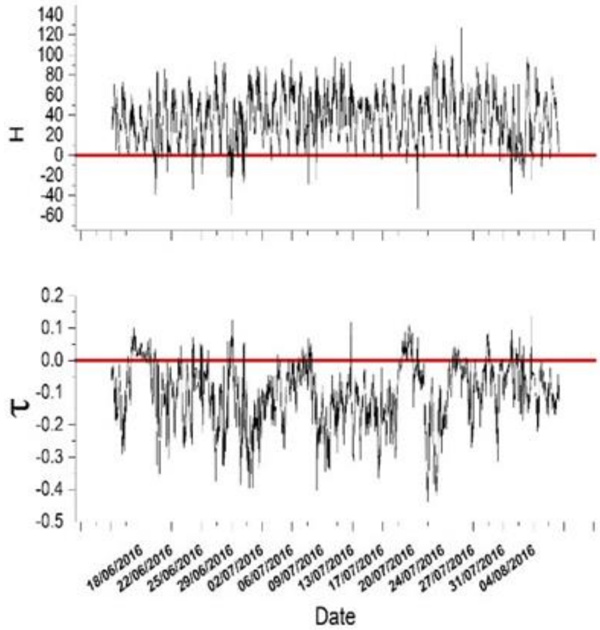


**Figure 7**: Variations of heat and momentum fluxes at daytime.

## Conclusions

The following points are the main concluding remarks for this study:

Maximum frequency of friction velocity at unstable conditions. Maximum value of $H$ during the study equals 127.6 $Wm^{-2}$ in 10:30 at 26/07/2016 and minimum value equals -58.9$Wm^{-2}$ in 07:30 at 29/06/2016. Maximum value of $\tau$ during the study equals 0.134535 $Nm^{-2}$ in 15:00 at 03/08/2016 and minimum value equals -0.4649 $Nm^{-2}$ in 03:00 at 01/07/2016.

There is an inverse relationship between $H$ and $\tau$.There is positive values of $H$ at nighttime that is because of heat capacity of materials which emits heat during the night.

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