Experimental Investigation Characteristics of the Related Wake of Linear Compressor by Hot-Wire Anemometer

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Abstract: In this paper, due to the importance of incoming flow turbulence intensity into combustion chamber, tripping wire effect on the flow wake has been experimentally investigated within a linear compressor cascade. Besides,effects of changes in the attack angle of compressor blades on the characteristics of wake are investigated. Investigation on the velocity, turbulence intensity and vortex frequency in the wake of blade in the attack angles of -10, 0 and 10 is done. In previous work the effects of a smaller angle of attack has been examined [1]. Therefore, to better understand the flow in the wake, more essential investigations appeared to be necessary for more angles of attack. Thus, two wires were implemented along each blade and their effects on average velocity, turbulence intensity and vortices frequencies were accurately considered.Increasing the angle of attack, leads toincrease inthe domain of wake and frequency at maximum amplitude, and the maximum Strouhal number.To do this, single channel hot wire anemometer was used to measure the wake parameters.

Keywords: Hot Wire Anemometer, Turbulence Promoters, Compressor Linear Cascade, Strouhal Number, Turbulence Intensity

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1 INTRODUCTION

Sometimes, some external sources,particularly geometrical obstacles and ups and downs bring about transition from laminar flow into turbulent flow abruptly in a very short time. In engineering applications, this method is called boundary layer tripping having various and extended usages despite its hazardous appearance.The turbulence existing in free flow which transmits from upstream toward downstream also has an identical effect in accelerating and/or delaying transition process from laminar flow into turbulent. The more turbulent the upstream flow, the shorter time required to transit from laminar into turbulent.

The effect of surface roughness on fluid flow depends on the relative size of rough elements compared to viscosity scale length of flow. Roughness effect could vary from minor and inconsiderable roughness having small scale length to substantial and totally effective for those with big scale length. The first and most apparent effect of surface roughness on the flow is its contribution to enhance the resistance against flow transition which is displayed as frictional drag increase in external flow or pressure loss arise in surrounded flow. Surface roughness is also capable of enhancing the rate of momentum, heat and mass transfer through the walls.

In process of boundary layer tripping of incompressible flow, there are some important and effective factors among which flow Machnumberis the most important one. 'd' is the length of roughness height to be considered. The velocity profile demonstrated in the position of x from the beginning of surface attack edge (or the equal position of roughness element implemented), velocity profile is corresponding to the situation in which there is on redundantas roughness along the flow direction. Reynolds number of roughness is defined in accordance to size of roughness height, local velocity exactly on top of the roughness of interest ,u_d and also kinematic viscosity υ [2]:

$$Re_d = u_d d/\upsilon \qquad (1)$$

Again,for Reynolds numberof roughness less than a specified amount, roughness has no effect on the position corresponding to the transition point from laminar type in to turbulent (which is definitely a point in downstream of implemented position). However, whenReynolds number of roughness reaches a specifically critical limit, transition of flow is transferred from its natural position to a point ahead (to the upstream). In subsonic flow velocities, if critical Reynolds number of roughness is reached, the transition point will be so close to roughness implemented in the position of interest. Numerous experimental results currently existing indicate that within subsonic range, critical Reynolds number corresponding to a rough element (with the height to width ratio of one) is approximately 600.

One can show that with increasing the Mach number of flow (or increasing compressibility effects of flow) the critical Reynolds numberrises to over 600. Implementing tripping wires, this study considers alsoblades of a linear compressor cascade and its effects on characteristics of the wake.

2 REVIEW

Few studies have been devoted to investigate the turbulence effects on combustion. The experimental work dealing with turbulence effectson combustion of tiny dropswas performed by Ohtaet al., [3]. Turbulence was produced using four fans embedded around the diameter of a cylindrical vessel. Based on their study, combustion rate reaches a peak in accordance to turbulence intensity and then reduces for bigger turbulence intensity rates.

Hashemi et al. analyzed effect of air turbulence intensity on forming nitrogen oxidein combustion of hydrocarbon and hydrogen fuel mixes numerically. Their results indicate that increasing the intensity of air turbulence reducesnitrogen oxide density in the domain where flam exists and also in the outlet of combustion vessel for the case of pure hydrogen fuel [4]. Among the studies carried out to analyzethe effect of trippingwireonairfoil, the following cases could be mentioned:

Zhang and Ligranistudied experimentally the effects of roughness and inlet turbulences on the airfoil wake in subsonic velocities and concluded that increase of surface roughness entails a significant rise in all wake figures including average velocity and turbulence intensity [5]. Dimensionless vortices frequency decreases at the same time, and inlet flow turbulences leavefewer effects on wake velocity. Later, they showed that wake figure depends greatly on surface roughness which is less sensitive to the inlet turbulence intensity.

Trimmer and Rooij in 2003 investigated the factorscontributed to tripping wire embedded on DU 93-w-zlo airfoil nose experimentally in wind tunnel [6]. The wires' diameters were selected equal to 1.2 mm and 5mm in conjunction with Reynoldsnumber chosen as 2×10^6.They embedded the wires at the positions of 1%c,0.5%c, 0.25%c and 0%c with respect to the level of airfoil pressure. The results of their study demonstrated that using the wire with the diameter of 2mm embedded at o.25%c contributes greatly to improve maximum capacity of airfoil lift whereas

thethinner wire at the same position does not display considerable effect leaving a wide blockage domain.
Freudenreich et al., [7] analyzed Reynolds effects within range of $10^6 - 10 \times 10^6$ along with roughness on DU 97-300 airfoil, applied in wind turbines using wind tunnel and numerical approaches. Once using roughening element includingtripping wire and zigzagtape, theyobserved that tripping wire embedded at z/c=0.3 from the airfoil nose slightly increases maximum lift coefficient compared to the smooth airfoil (It also caused a decrease in $(c1/c_d)_{max}$).
Fukudome et al., analyzed efficiency of NACAOOl8 symmetrical airfoil using tripping wire [8]. Embedding wire of interest at airfoil nose, they showed that using tripping wire increases lift coefficient in wider angles of attack. They also demonstrated that wire of interest is the reason for improvement of stall angle in airfoil without increasing drag coefficient. On the other hand, in wider angles of attack for wireless airfoil, larger separation is observed which is limited using wire, and lift force as well as airfoil efficiency will be enhanced.
Huber and Mueller also found out in their experiments that using tripping wire at the position of maximum thickness of Wortmann FX 63-137 airfoil decreases harmful effects for maximum lift [9]. They made clear that locating wire at this position could lead to a decrease in minimal drag coefficient.
James and Truong and also Igarashi in another work conducted an experiment survey about effects of different diameters and various positions of turbulence–making on inlet flow passing on cylinder Reynolds number ranging between 10^4 to 10^5 in conjunction with diameters of turbulence–making wire varying within 0.6%D–6.3%D [10], [11]. They concluded that using turbulence- making wire with the bigger relative diameter make the transition possibleto happen in lower Reynolds number. They also concluded that with increasing wire's diameter, the optimum location for embedding the turbulence–making wire aimed at reducing drag force more toward the stagnation point.
Nebraska and Batill carried out investigations oncylinder equipped with turbulence–making wire and studied effects of embedding wire at cylinder angles of 0-180 on features of flow, drag, and lift coefficients and the coefficients contributing flow vary in a particular range of angles relevant to position of wire embedded on cylinder in such a way thatStrouhal number and drag coefficient follow an opposite trend with respect to each other [12]. In addition, Pearcey et al., concluded that for changing low-Reynolds flow to the critical one, it is necessary for diameters of wire to be altered too [13].
Moreover, Zhou et al. conducted a numerical investigation in this fieldin 2007 [14]. They devoted their study to two sets of Reynolds numbers. Comparing effect of different Reynolds numbers, they observed that once Reynolds Number increases, optimum angle for embedding wire aimed at reducing drag coefficient moves toward the stagnation point of flow around the cylinder.In 2010, Mahbub Alam et al., also investigated parameters of flow using turbulence-making wire in a specific range of angles on the cylinder in a symmetrical way [15]. In thisstudy, they witnessed 5 flow regimes passing on the cylinder with respect to change of position where tripping wire located in which each flow parameter varied according to its particular trend. Besides, in this flow based on variation of Reynolds Number corresponding to the passing flow on the cylinder, optimum position for embedding the tripping wire aimed at reducing drag coefficient also changed.

3 MOTIVATION

Applying tripping wire particularly in high Reynolds numbers causes substantial unclear changes at the separation point. Dynamic fluctuations, which are natural in turbulent flows, could bring about mixture and intense exchange of flow quantities especially momentum, heat and mass. Consequently, turbulent flows are supposed as high (dissipation) flows with high friction coefficient (and heat and mass transfercoefficients) compared to laminar flow. Larger scale of fluctuation would cause larger momentum and heat exchange. Therefore (consideringincreased pressure loss in turbulent flow), when dealing with heat and mass transfer,making flow turbulent until increased pressure loss would not lead to inefficiency, and uneconomic results in project is always noted by engineers.
The purpose of this study is toinvestigate the effects evaluated to embedding turbulence–making wire on blades of linear compressor cascade on characteristics of wake corresponding to subsonic compressor cascade in such a way that changing trend of velocity, turbulence and velocity moment profiles are eventually compared with simple compressor cascade.This survey provides new information about influence of turbulence–making wire on wake of compressor cascade.

4 EXPERIMENTAL EQUIPMENTS

The experiments of this study have been carried out in a wind tunnel of open circuit type with1kw power and blowing. For this purpose, a vessel with 150 cm length, 40 cm width and 15 cm height, from poly glass material was produced (Fig. 1). The velocity of wind tunnel may be altered to monitor fan speed specified in the tunnel from 0 to 30 meters per second. In this analysis, generative power for each experiment has been selected equally. Accordance to the characteristics of wind tunnel, maximum nominal turbulence of free flow is 0.1% for this arrangement which is counted as highly accurate for wind tunnel.

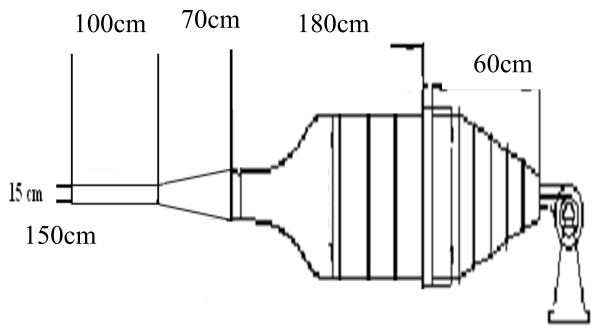

Fig. 1 Wind tunnel schematic andvessel experimental setup

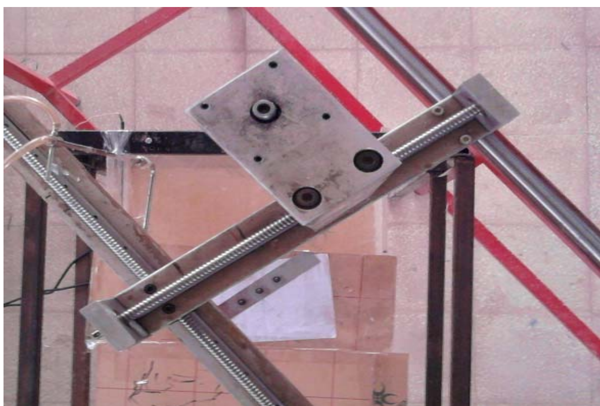

Fig. 2 location of probe displacing system on compressor cascade

Fig. 3 Placingtripping wires on compressor's blades in wind tunnel

For measuring flow parameters, anemometer of constant-temperature hot wire has been employed which is able to measure mean velocity going out of cascade. Wind tunnel and the arrangement of hot wire anemometer were both manufactured in Fara Sanjesh Saba Corporation. The experiments accomplished through a unidimensional probe having a sensor with the length of 1.25 mm and diameter of 5µm. Experiments were performed in winter and calibration arrangement was accomplished at environmental temperature of 15°C. Although environmental temperature of laboratory was fluctuating during the day, however variation within 2^oC is acceptable.

A displacing device with displacement accuracy of 0.01 mm and 3 degrees of freedom has been used to do the investigation at various points. This mechanism moves parallel to the embedding line of blades to record the required data (Fig. 2). The mechanism described above has been embedded on frames separated from bases of wind tunnel to prevent any possible vibration of tunnel body from transferring to displacing mechanism and enhance sampling quality. The tested compressor cascade has 3 blades of KH-4356 type located with standing angle of 40^o in test vessel (Fig. 1).The blades tested have height of 115 mm and chord's length of 3.3 cm. The wires utilized to make turbulence have diameters of 2 mm placed in the middle of the part at both sides of the blade as shown in Fig. 3.

5 RESULTS ANALYSIS

This survey investigates the effect of tripping wire on parameters corresponding to the wake and cascade turbulences of a linear compressor. Since moving from back of the airfoil wake is disappeared due to the fact that the existing shear layer is influenced with the free flow, and consequently the free flow attempts to damp shear layer called the wake, sampling was carried out in a distance from the trailing edge at x/c =0.5 (x is the distance between probe position andtrailing edge of airfoil, and c is the length of blade chord) and also at attack angles of I =-10 , I =0,I =10 [15].

The experiments were conducted at two stages. First, compressor cascade was roughly studied at wind tunnel, and wires with diameters of 2mm and lengths of 115 mmwere positioned subsequently in central line of blades, one at top surface and the other at the bottom.Following these,the blades were put in the experimental vessel.

In this experiment,(embedding) stage angle of blades were selected at $40^o$and wake parameters were measured at attack angles ofI=-10, 0,10 along with ReynoldsNumber of 45500 which was calculated based on length of blade chord, velocity of free flow and dynamic viscosity at 15^oC temperature (Fig. 4).

According to Eq. (1), it is possible to obtain roughness Reynoldsnumber originating from positioning of tripping wires, and compare them with critical Reynolds number considering roughness height and local velocity of flow on the wire. With regard to the measurement of local velocity using hot wire anemometer$u_d = 1z\ m/s$and roughness height (diameter of tripping wire) of d=2 mm, value of roughness Reynolds equals to $Re_d = 2068$ which is much greater than the critical Reynolds Number value ($Re_{cr} = 600$).

From [2], it is possible to expressthat the position of transition point from laminar to turbulent has been displaced to a point closer to trailing edge of blade.Due to their geometric shapes (as cylindrical), and apart from measuring velocity along the flow direction (U), one-element sensors are able to detect velocity component of perpendicular to flow directionwhich is V and display magnitude of flow velocityas illustrated byw in Eq. (2).

$$\left(w = \sqrt{u^2 + v^2}\right) \quad (2)$$

As the distance from back of the modelincreases, the measured velocity using sensor approaches the value of the velocity along the flow (U). Since in this study sampling was carried outat the position $x/c = 0.5$(close to the trailing edge of blades), the expressions ofw andw$_{ref}$ have been used for recorded velocity with sensor and velocity of free flow,respectively.

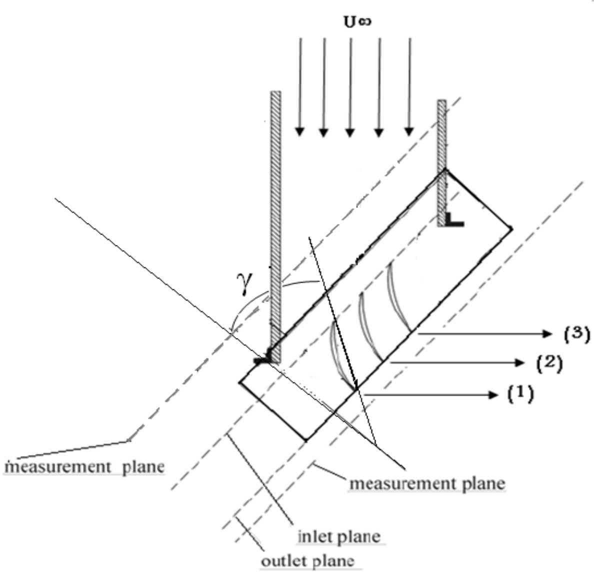

Fig. 4 Schematic of positioning (γ)of blades in compressor cascade

5.1.Consideration of Dimensionless Mean Velocity

Since central blade of cascade is affected with its adjacent blades,the current study concentrates on its resulting profiles. As it is clear from Fig. 5, with increasing attack angle, velocity profile leans more to the left side, contracts and seems to disappeargradually. This event is repeated in cascade within the blades with wire, although velocity profiles are more stretched anddisappeared at higher attack angles in this case (Fig. 6). The disappearancephenomenon of velocity profile is due to the fact that increasing positioning angle changes the cascade to the turbine one, and reducing this angle changes it to the compressor cascade.

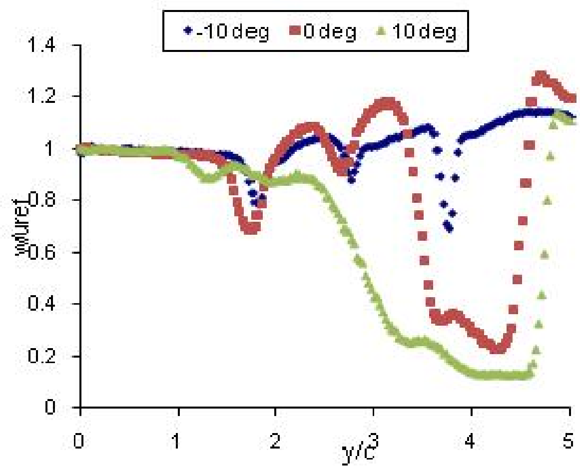

Fig. 5 Comparison of dimensionless mean velocitiesat 3 different attack angles (tripping wires-free cascade)

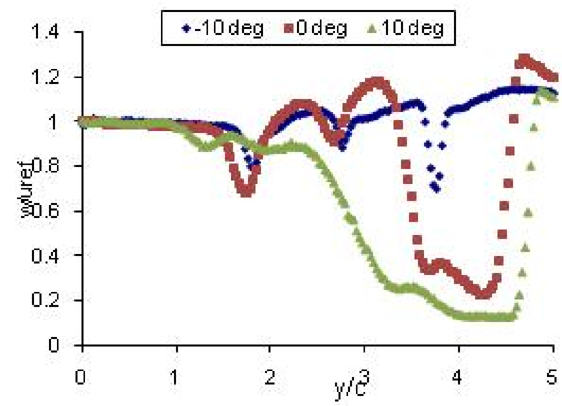

Fig. 6 Comparison of dimensionless mean velocitiesat 3 different attack angles (cascade in presence of tripping wires)

Creating turbulence with wires in boundary layer entails a separation at further distance from attack edge and a decrease in wake width [11]. This effect is qualitatively similar to natural transfer of turbulence in which increase of velocity in raising and preceding situations (in front of stagnation point) brings aboutdevelopment on cylinder in a turbulent flow because of being random and irregular [16]. A series of subsequent events,sometimes, occur perpendicular to the direction of main flowbecause of movements of substances and presence of turbulence or fluctuation in flow as well. For this reason, momentum of layers near a wall which have lost part of their energy due to ruin nature of the flow was boosted with more energetic layers on top, and this lead to compensate part of the mentioned lost momentum of fluid adjacent the wall.

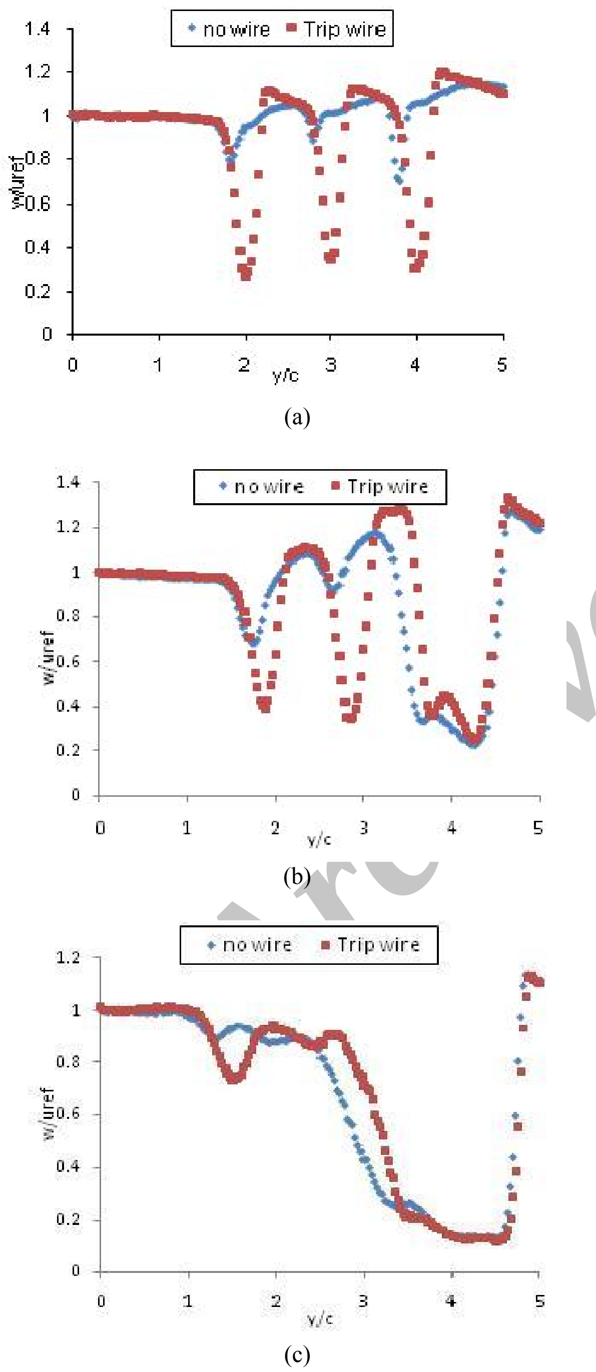

Fig. 7 Comparison of non-dimensional mean velocity of cascade in presence and absence of tripping wires at different attack angles: a) I =-10, b) I =0 and c) I =10

Once the tripping wires were positioned, the non-dimensional velocity profiles were displaced to the right, and also a displacement at the pick was observed which reached its maximum value (0.6) at attack angle of 0° (Fig. 7).

5.2. Consideration of Turbulence Intensity

Evidently, turbulence intensity parameter is calculated from the following Eq. (3).

$$\%Tu = \frac{\sqrt{u'^2}}{U_\infty} \times 100 \quad (3)$$

Turbulence velocity is observed plus the oscillation velocity u near the body and measured by the sensor positioned in flow direction. Based on the preceding statements, sensor represents quite maximum of turbulence at the position where sampling has been carried out (x/c=0.5).Regarding the turbulence intensity of central blade, it could be said that according to Fig. 8, as attack angle increases, maximum of turbulence is enhanced and its peak is displaced to the right as well.

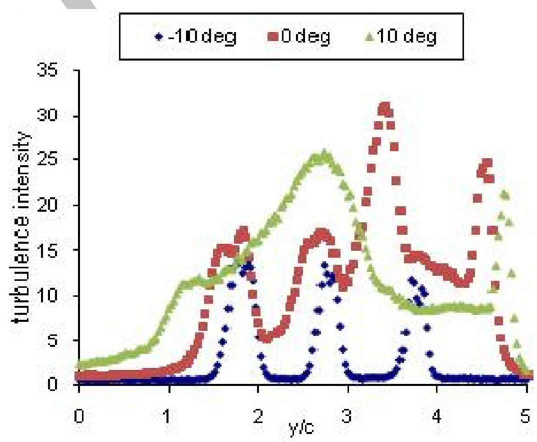

Fig. 8 Comparison of turbulence intensities at three different attack angles (cascade in the absence of turbulence-making wires)

As a matter of fact each moving particle of fluid always tends to retain its momentum. once a particle of fluid inside the boundary layer (without the required potential and just because of the unsteady nature of flow) mutate from a low-momentum layer to a high-momentum one or vice versa, the particle, to gain its first value, in its new position, moves gently in a very small scale opposite to the direction of momentum from the corresponding layer.

The set of these movements along with flow leaning to satisfy continuity law, leads to form eddy. The presence of eddy may result in corresponding distribution of momentum, turbulence, thermal energy, pressure and temperature within the domain. In a flow without the gradient in mean velocity profile, an oscillation of velocity component would not necessarily result in an eddy and the perturbation gets damped under the effects of viscosity in a very short time.

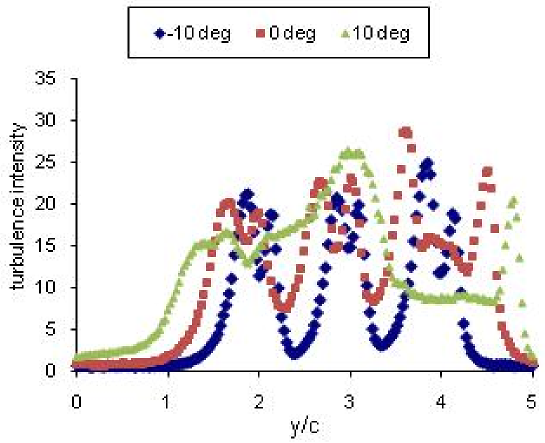

Fig. 9 Comparison of turbulence intensities at three different attack angles (cascade in the presence of tripping wires)

Using tripping wires would increase maximum of turbulences in blade wake and would also change the figure from one-peak to two-peak case. The width of figure in all three attack angles also has risen unlike the velocity profile in which the widths of figure decrease after positioning the wire (Fig. 10). As the attack angle increases, the width of profile also enlarges which according to what mentioned earlier, the bigger the scale in which the turbulence takes place, the more the amount of momentum and heat transfer occurs (Fig. 9). Therefore, in dealing with heat and mass transfer when it comes to consider the enhanced pressure loss in turbulent flow, making flow turbulent in desirable unit would not result in inefficiency and loss of economy in project.

5.3.StrouhalNumberConsideration

Since the frequency response of hot wire anemometer is faster compared to other types of the system, it is appropriate to use it to process the rough results and display reasonable graphs from the spectrum analysis of the flow wake. Considering the fact that hot wire anemometer system saves information of each point as a large amount of data, it is impossible to provide information point by point from all flow ones. Instead, spectrum analysis of velocity components directing in x, y and selective points of flow wake manifests to some extent the wake dynamics.

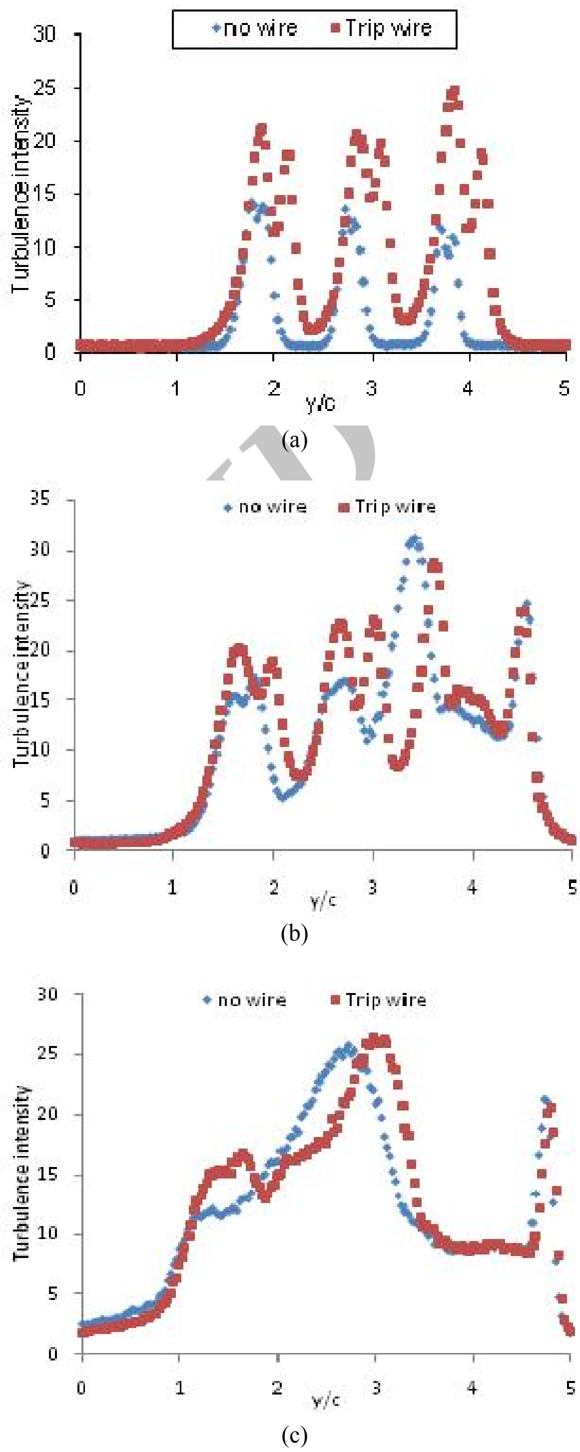

Fig. 10 Comparison of turbulence intensities of cascade in presence and absence of tripping wires at different attack angles: a) I =-10, b) I =0, c) I =10

Strouhal number is a dimensionlessnumber which presents the frequency of oscillations related to Carmen vortices formed in the back of the model as a dimensionless value.It is defined as follows:

$St=f^*x/W_{ref}$ (4)

Where f, c and W_{ref} are frequency vortices of model, blade chord length and velocity of fluid free flow, respectively. The frequency of vortices formed in the back of the model could be obtained through the sensor of hot wire anemometer in wind tunnel.

5.3.1. Specification of the Vortex Frequency using Hot Wire Sensor

Hot wire sensor receives values of oscillations related to fluid flow in wind tunnel as perturbations in time,i.e., in time domain and their transformation into frequency domain using Fourier series transform and finally displaying on the screen as oscillation amplitude versus frequency. The sampling frequency was set to 5 kHz in the associated wind tunnel (Fig. 11).

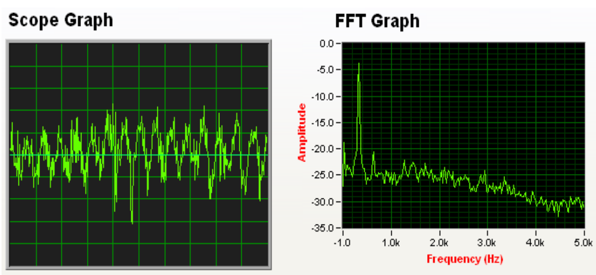

Fig. 11 Flow oscillation in time domain on left and in frequency domain on the right

In the frequency domain, amplitude of all flow oscillations (with different frequencies) measured with sensoris possible to be observed.From all oscillations in the back of the model, it is clear that oscillations corresponding to Carmen vortices have the highest amplitude. Therefore, the frequency of the highest amplitude is in fact the value of Carmen vortex frequency (Fig. 12).
From Fig. 12, it could be inferred that in cascade of blades being turbulent at all attack angles, the maximum frequency stands near the point at y=50 mm. in other words, it is in a position between blades 1 and 2 which varies with respect to change in attack angle. Moreover, it might be concluded that increasing the attack angles would result in the flow frequency decrease which is apparent at the attack angle of I=10. Providing turbulence totally causes a reduction of frequency in maximum amplitude and in Strouhal number as a result. Of course, the reduction is more significant at the attack angle of I =-10 compared to angle of I = 0.
At the attack angle of I=10, the Strouhal number increases by adding the wires and this means that roughness makes Carmen vortices to get higher frequency in the back of cascade (Fig. 12-c). The value of the Strouhal numbers corresponding to various attack angles are shown in table 1 asobtained from Eq. (4).

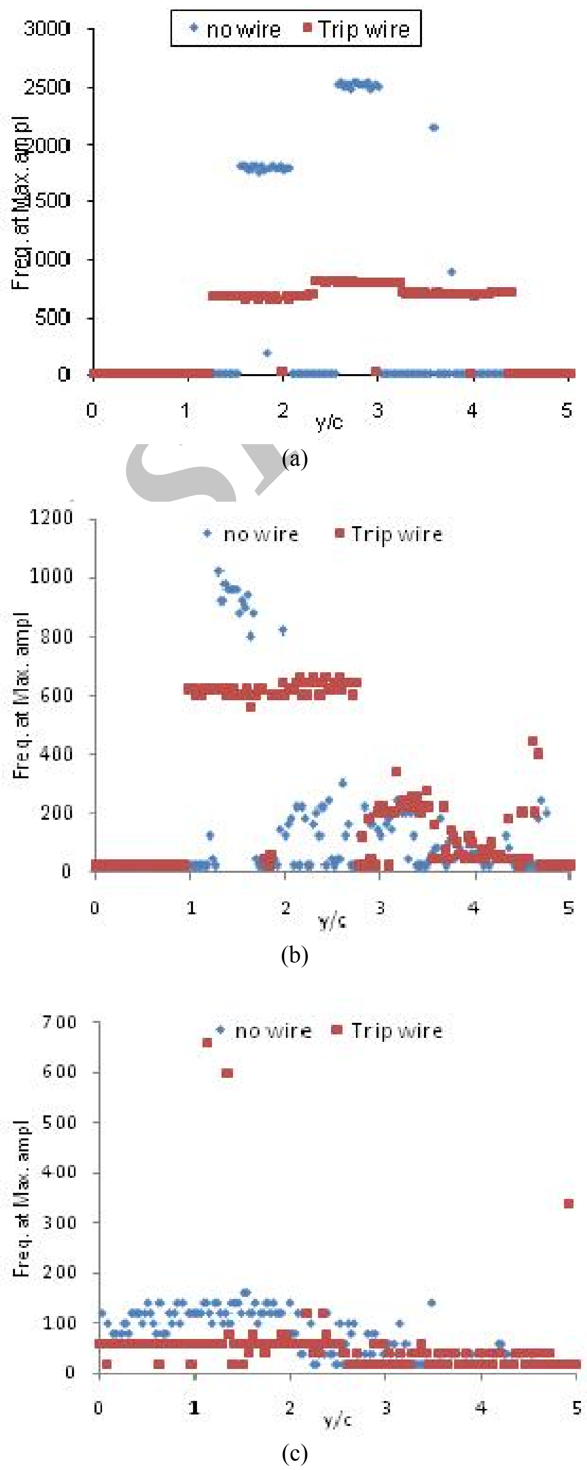

Fig. 12 Comparison of flow frequency at the maximum amplitude for cascade in the presence and absence of tripping wires at different attack angles: a) I=-10, b) I=0, c)I =10

Sampling in this study have all been carried out at the velocity of U=20 m/s and the position of x/c=0.5 from the leading edge of blade. However, Shad Aram et al. with performing the spectrum analysis of flow concluded that as Reynolds number doubles, the frequency of vortices formation does not change considerably and also as the model moves far from the flow direction, frequency spectrum density of velocity oscillations decreases.

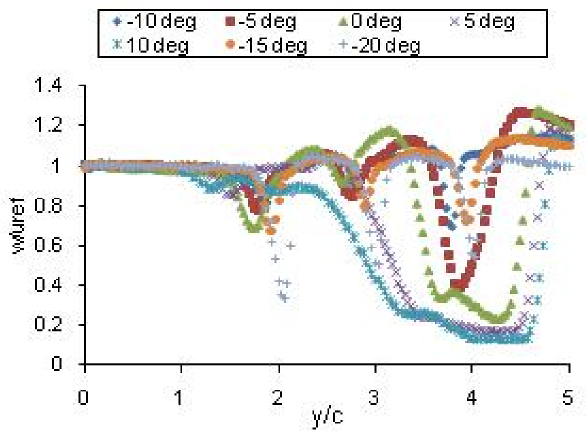

Fig. 13 Comparison of dimensionless mean velocities at different attack angles (tripping wires-free cascade)

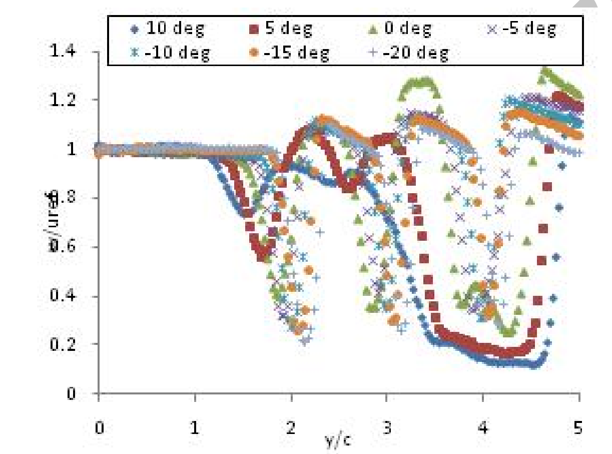

Fig. 14 Comparison of dimensionless mean velocities at different attack angles (cascade in presence of tripping wires)

Table1 Values of Strouhal numbers for compressor cascade at different attack angles

	No wire			Tripping wire		
Incidence angle	-10	0	10	-10	0	10
Frequency	2573	1020	150	940	619	365
Strouhal number	4.2	1.6	0.24	1.5	1.0	0.65

6 COLCLUSION

In this study, a linear compressor cascade having three blades were considered in two situations, first, as simple and then after positioning tripping wires on blades in wind tunnel with the Reynolds number of 45500. A system of hot wire anemometer was utilized to measure the flow parameters. Based on the arguments mentioned above, the following conclusions might bederived:

- As the attack angle increases, velocity profile is displaced to the left and at the same time shrinks and disappears. Providing turbulence using wires in boundary layer resulted ina separation further from the leading edge and a reduction also in wake width.
- Once the wires were positioned, dimensionless profiles were displaced to the right at all angles and also their peaks were shifted in which the displacement reached its maximum value of 0.6 at attack angle of I=0.Perturbing the boundary layer increased the maximum turbulence in blade wake, raised the plot width and changed the shape of turbulence figure from one-peak case into two-peak one. Increasing the attack angle would reduce the flow frequency which is apparent at attack angle of I=10. Using tripping wires would reduce the frequency at maximum amplitude and as a result the Strouhal number would decrease, which is more considerable at attack angle ofI=-10 compared to other attackangles.
- Increasing the angle of attack, increases the domain of wake, increases the frequency in the maximum domain, and increases the maximum Strouhal number consequently.

Nomenclature

c	Blade chord (mm)
U	Horizontal component of flow velocity (m/s)
D	Diameter cylinder
U_∞	Recorded inlet flow velocityby pitot probe (m/s)
d	Wire diameter (mm)
u'	Horizontal velocity turbulent component (m/s)
E	Watson bridge high voltage (V)
u_d	Roughness local velocity (m/s)
E_r	Wetson bridge high voltage in T_r(V)
f	Current frequency in max. Amplitude (Hz)
i	Incidence angle (deg)
Re_{cr}	Critical Reynolds number
NO	Carbon monoxide
$\%Tu$	Percent of Turbulence intensity
Re	Reynolds number
W_{ref}	Velocity of free stream (m/s)

Re_d Roughness Reynolds number
C_d Drag coefficient
St Strouhal number
C_l Lift coefficient
x Distance from leading edge (mm)
v' Horizontal component of flow velocity (m/s)
V Vertical component of flow velocity (m/s)
y Axis parallel to the direction of the blade (mm)
n Calibration constant and power of correction coefficient
$W = \sqrt{U^2 + V^2}$ Mean velocity recorded by probe (m/s)

Greek Nomenclature

γ Stagger angle (deg)
ν Dynamic viscosity (m^2/s)

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