Frequency and Spatial Dependence of Cross Correlation Velocimetry

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Abstract

This study analyses the frequency and spatial dependence of Cross Correlation Velocimetry (CCV) towards the measurement of fire induced flows. CCV uses temperature-time records from a pair of thermocouples, one downstream of the other, cross-correlated to determine the flow's velocity and is based in principle on the "frozen eddy" concept in turbulent flows. In between 1975 and 1980 Cox et al. [1] performed a series of experiments that showed that spatial and temporally resolved velocity measurements could be achieved by means of CCV. These types of velocity measurements are crucial in understanding ceiling jets, the role of sprinkler activation, and also in micro-gravity fire induced flows that conventional techniques cannot measure. However, the high cost associated with expensive analogue correlators available those days caused the CCV technique to gradually phase out after the advent of the bidirectional probe which was significantly cheaper and more robust in design. There have been vast improvements in data acquisition techniques, digital signal conditioning, filtration of random noise, as well post processing statistical packages which allow better and faster cross correlation of two random signals. This study is a first step towards applying these technological advantages to this outdated technique.

The CCV probe's accuracy is most sensitive to the thermocouple wire diameter, separation distance, and speed of data acquisition (sampling frequency). This study presents a parameter sensitivity analysis that includes the measurement of axial components of velocity in a heated turbulent jet with a velocity of 1.1 m/s with the sampling frequency, and probe separation distance adjusted independently (thermocouple wire diameter is kept constant).

Nomenclature:

A	=	Surface Area	(m^2)
C_p	=	Specific Heat	(J/(kg °C))
d	=	Distance between Thermocouples	(mm)
f	=	Sampling Frequency	(Hz)
h	=	Average Convective Heat Transfer Coefficient	(kW/m^2)
R_{xy}	=	Cross correlation function of x(t) and y(t)	(-)
t	=	Time	(s)
T	=	Averaging Time	(s)
T_{max}	=	Maximum temperature	(°C)
T_{ave}	=	Average Temperature	(°C)
v	=	Velocity	(m/s)
V	=	Volume	(m^3)
$x(t)$	=	Temperature profile	(°C)
$y(t)$	=	Temperature profile	(°C)
ρ	=	Density	(kg/m^3)
θ	=	Non Dimensional Time	(ND)
τ	=	Time lag	(s)
τ_s	=	Spacing Lag	(-)
τ_R	=	Response Time	(s)

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Introduction:

Accurate measurement of temperature and velocity fields created by fire plumes is vital in quantifying the thermal impact of a fire. Both play a major role in the prediction of smoke detector and sprinkler activation, design of smoke venting systems, and estimation of egress times. In addition, accurate knowledge of temperature and velocity of fire induced flows is crucial in the determination of structural integrity in a fire environment. While temperatures can be measured accurately using array's of thermocouples, the field of fire science lacks an economical method of measuring velocity fields [2].Table 1 shows velocity measurement methods currently in use. Bi-directional probes have been used successfully to determine the velocities in doorways and other areas where the general direction of the flow is known. The disadvantage of this type of system is that the probes are large (causing flow obstruction), and suffer from calibration problems. In addition, the bidirectional probe becomes inaccurate at flows lower than 0.5 m/s [3]. The pitot tube is not heavily used in the fire field due to the small size of the pressure tap holes which can become clogged with soot. The hot wire anemometer is slow to correct for temperature changes and suffers from a limited range and calibration problems. The laser Doppler anemometer requires seed particles which are easily added to laboratory scale tests but is difficult for large scale tests. Laser systems are also prohibitively expensive for many fire tests situations.

This work tests a methodology for measuring velocity which was proposed in the early 70's by Cox [1] that uses the cross correlation of two temperature profiles from a pair of thermocouples, one downstream of the other, to determine a flow's velocity. The cross correlation Velocimetry (CCV) technique is based in principle on the "frozen eddy" concept in turbulent flows put forward by Taylor in 1938 [4]. Taylor hypothesized that in a turbulent flow, there are eddy structures that retain their shape and characteristics over some time and space. In other words, an eddy can be considered frozen for a limited time over a given space. If these eddy structures can be identified and traced, then the most probable mean velocity of the flow can be estimated as the weighted average of the velocities at which the eddies are moving. Numerous investigations of turbulent flows have shown the movement of eddy structures in a flow to represent the true mean flow velocity [5, 6].

Cox was the first to verify the "frozen eddy" hypothesis in a non-isotropic ceiling jet flow thereby developing the CCV probe [7]. In between 1975 and 1980 Cox *et al*.[1, 7-9] performed a series of experiments that showed that spatial and temporally resolved velocity measurements could be achieved by means of CCV. The associated errors reported by Cox were of the order of ± 15%. Since the velocity measurement is dependent on "phase" and not "amplitude" of the signal, systematic errors in temperature measurement such as radiation and conduction losses does not affect velocity measurement. In spite of this significant advantage, the probe designed by Cox was limited by the speed of data acquisition. In fact, the main problem was the high cost associated with expensive analogue correlators available in those days. This caused the technique to gradually phase out after the advent of the bidirectional probe which was a lot cheaper and more robust in design.

Subsequently these probes have been used for fire applications by Motevalli et al. [10], Dupuy et al.[11, 12], Marcelli et al. [13], and Santoni et al. [14]. These studies have established further limitations associated to the sampling frequency and time constant of the thermocouple which is related mainly to the wire diameter and material properties of the thermocouple (conductivity, specific heat and density). The problems observed by Cox due to data acquisition were only partially solved leading to 1-D measurements that achieved higher accuracy (order of ± 10%).

The CCV can be used over a wide range of temperatures, it does disturb the air flow anymore than the thermocouple trees and the probe can report temperature as well as velocity. Since most fire tests use thermocouple trees, the CCV technique allows capability of measuring velocity for basically the cost of a single extra thermocouple for each velocity point. The CCV probe can provide real time velocity measurements in flows up to 800 °C without causing major disruptions to the flow. It is inexpensive to construct and has the potential of yielding high accuracy with the recent advances in signal conditioning and data acquisition methods [15], [16]. There have been vast improvements in data acquisition techniques, digital signal conditioning, filtration of random noise, as well post processing statistical packages which allow for better and faster cross correlation of two random signals. So far the probe has been tested at maximum sampling rates of 700 Hz[16]. It is possible to increase this rate to more than 3000 Hz. To get maximum information from the flow one needs sensors with minimal response time. There are various techniques to achieve this: for example using noble metals such as Platinum for thermocouple junctions, amplifying the signal using signal conditioning etc. These methodologies have never been tested thus far.

Table 1: Velocity measurement methods widely in use. Device is compared with the operating principle

**** technique proposed in this study***

Device	Operating Principle
Bi-directional probe (BDP)	ΔP
Pitot tube	ΔP
Hot wire anemometer	ΔT
Laser Doppler Anemometer (LDA)	Scattered Shifted Light
Cross Correlation Velocimetry (CCV)*	Temperature Fluctuations
Particle Image Velocimetry (PIV)	Scattered Light
Phase Doppler Particle Analyzer (PDPA)	Scattered Shifted Light

Operating Principle of CCV:

Only the major points of the method are presented here. The reader can refer to Cox [8] (1977) for further details. Figure 1 shows a theoretical temperature profile that is obtained from two thermocouples that are spaced *r* cm apart. Since r is small (less than 30 mm), the two thermocouples sense the same thermal fluctuation. However, the temperature time record of the thermocouple located downstream is shifted by a time τ seconds as shown in Figure 1. If τ can be accurately estimated the velocity of the flow is simply given by Eq. 1:

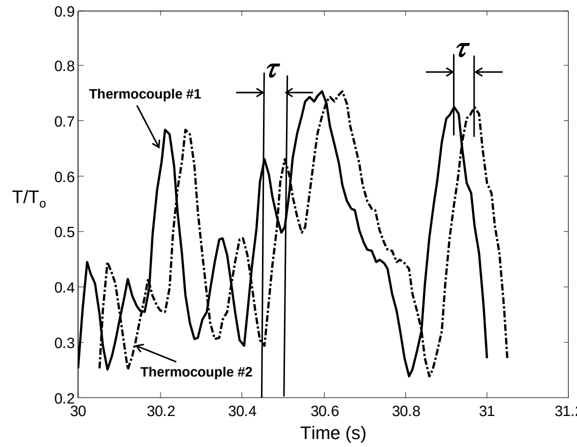

Figure 1: Example of compensated temperature plot from two thermocouples placed *r* cm apart. velocity = r/τ.

$$v = r/\tau \,. \tag{1}$$

τ is determined accurately by using the correlation concept where the degree of association between certain variables is to be measured [7]. To calculate the time for a turbulence eddy passing between the pair of thermocouples the temperature profiles are cross correlated using Eq. 2,

$$R_{xy}(r,\tau) = \lim_{T\to\infty} \frac{1}{T}\int_0^T x(t-\tau)y(t)dt \,, \tag{2}$$

Where the two thermocouple signals are represented by x(t) and y(t), and x(t-τ) is the delayed version of signal x(t). T is the averaging time/sampling period over which the signal is correlated. Finding the delay between the time when an eddy passes from one thermocouple to the other requires finding the lag which maximized the correlation function R_{xy}. To calculate the time for the turbulence to pass between the two thermocouples the lag is multiplied by the sampling rate. For the results presented in this paper the averaging time/sampling period was set to 15 seconds to follow the procedure reported by Motevalli [17].

CCV is affected by seven main factors: sampling frequency, TC response time, TC separation distance, turbulent eddy size, soot accumulation, equality of TC time constants, and sampling period. The two factors examined in this study are frequency and TC separation distance. A systematic study of the influence of other factors is currently underway at the WPI Fire Science Laboratory.

Sampling frequency affects the CCV technique because if data is not recorded fast enough the temperature changes in the turbulent eddies will not be represented correctly by the temperature profile of each thermocouple. The maximum viable sampling frequency is determined by the time constant of the thermocouple. This is due to the thermal inertia of the probe. Sampling to fast will simply result in longer data profiles with no increase in accuracy. Using a lumped analysis the time constant for a thermocouple is determined from Eq. 3. This is valid due to the small point like nature of the thermocouples being used [17].

$$\tau_R = \frac{\rho c_p V}{hA} \quad (3)$$

The TC response time can be changed by adjusting the size of the thermocouple bead, using materials with smaller specific heats such as noble metals, or using materials with smaller densities. Type E type thermocouples are used because of they have the highest output per degree temperature change of standard thermocouples **(**approximately 60mV/°C and temperature range between -270 to 1100°C **)**. The optimum spacing of the two thermocouples is a function of the flow velocity due to several factors. First if the TC's are too far apart the eddy will shift between the TC's, secondly if the thermocouples are too close together the downstream thermocouple will be in the wake of the upstream TC. Also, at smaller spacing's small errors in the lag spacing calculation results in large errors in the velocity calculation when the separation distance is small. The size of the turbulent eddy plays a significant role in the probe accuracy. According to Motevalli [17] the accuracy of the CCV technique increases as eddies become larger and stronger. Changes in bead diameter can be caused by soot accumulation on the probe. This will affect the time constant of the probe and could make it respond to slowly to make accurate velocity measurements. If soot builds up unevenly on the two probes then their respective time constants will become different due to the change in size and thermal mass. If the two thermocouples have different response times the lag calculated will result in the measured velocity being to low or to high depending on which TC has the increased response time [17]. The sampling period can affect the accuracy of the CCV technique. To measure the most accurate flow profile the sampling period should be long enough to identify the lag in the signal but short enough to show changes in the flow velocity. The sampling period will determine the speed at which real time measurements can be updated using this technique.

In a real fire scenario, turbulent eddies are generated by the buoyant entrainment of the fire itself. In a forced flow jet, as used in this study, the turbulence must be induced and can be controlled through the use of either obstructions in the flow or a mesh put over the turbulent jet. For an obstruction in the flow the size and shape are the critical parameters to determine the eddy size and for a mesh the spacing between wires will determine the eddy size.

This study examines the effects of sampling frequency and thermocouple separation distance on the CCV technique. By using a heated axisymmetric jet and taking measurements along the vertical axis these parameters can be adjusted to test their influence on velocity measurements separately. Measurements from a hot wire anemometer is taken as the true flow speed and used to calculate the error in the CCV technique.

Experimental Setup:

The experimental setup comprises of a variable speed heated axisymmetric jet surrounded by a Plexiglas cage. The temperature is controlled by a rheostat which controls the current powering two resistance heaters aligned in series inside of the axisymmetric jet. The amount of air injected into the jet is controlled by a regulator connected to the lab air supply. As shown in figure 2, a set of E type thermocouples, with bead diameters of 7.62×10^{-5} m (0.003 inches) are passed through 0.15 m (~6 inches) of ceramic insulation and glued in place. A set of digital calipers mounted parallel to the jet are used to change the spacing between the probes. The thermocouple wires are shielded to damp the disturbance caused by the electromagnetic (EM) fields generated from the heating elements. Since the cross correlation only depends on the phase of the signal and not on the amplitude, cold junction compensation on the thermocouples is not included. A NI DAQ Data Acquisition system comprised of a NI SCXI-1000 Chassi, NI SCXI 1600 A/D converter, NI SCXI-1102 amplifier, and a NI SCXI 1301 simultaneously sampling unit is used to sample the data at a rate of 1000 to 3000 Hz. An Omega PMA-902 hot wire anemometer is used to compare the velocity obtained by CCV technique. Data is collected at spacing's of 5, 10, 15, 20, and 25 mm and one minute of data is recorded for each test. These tests are done at a steady velocity of 1.1 m/s with the upper, stationary thermocouple, 63 mm from the exit of the jet.

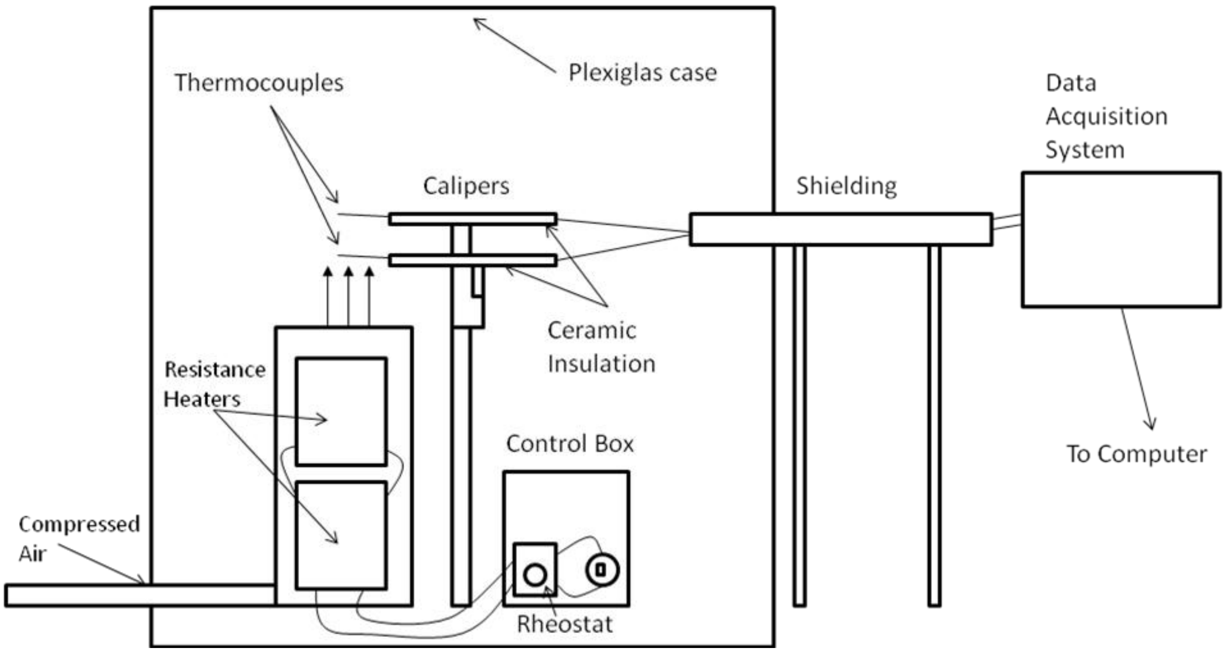

Figure 2: Experimental set up comprising of a heated axisymmetric jet. Two E type thermocouples with bead diameters of 7.62x10^{-5} m are shown mounted on a set of digital calipers to adjust the spacing distance from 5mm to 25mm.

Results and Analysis

Figure 4 shows part of a non-dimensional adjusted temperature history curve highlighting the offset of the two temperature profiles. The temperature profiles were nondimensionalized using Eq. 4 given by,

$$\theta = \frac{T}{T_{\max}} - T_{ave} \ . \quad (4)$$

As shown in Figure 4, it is difficult to quantify the lag between two temperature profiles over a range of temperatures directly necessitating the need to apply a cross correlation to find the overall lag between two temperature profiles.

Figure 4b shows the results of cross correlating a 15 second set of data taken at a velocity of 1.1 m/s, with a 15mm separation distance between TC probes, and a sampling rate of 1000 Hz. The cross correlated signal, R_{xy} has a peak at a lag of 11 data samples which corresponds to a velocity of 1.25 m/s.

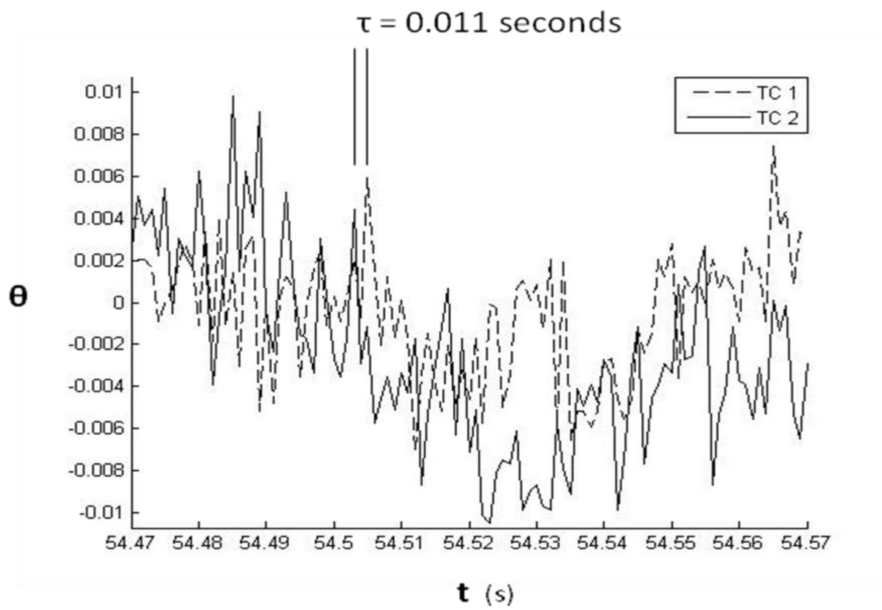

Figure 4: Data taken at a sampling rate of 1000 Hz and a TC separation distance of 15 mm, which has been non-dimensionalised by dividing by the maximum value in each profile and subtracting the mean. τ of 0.011 s is shown between two distinct peaks.

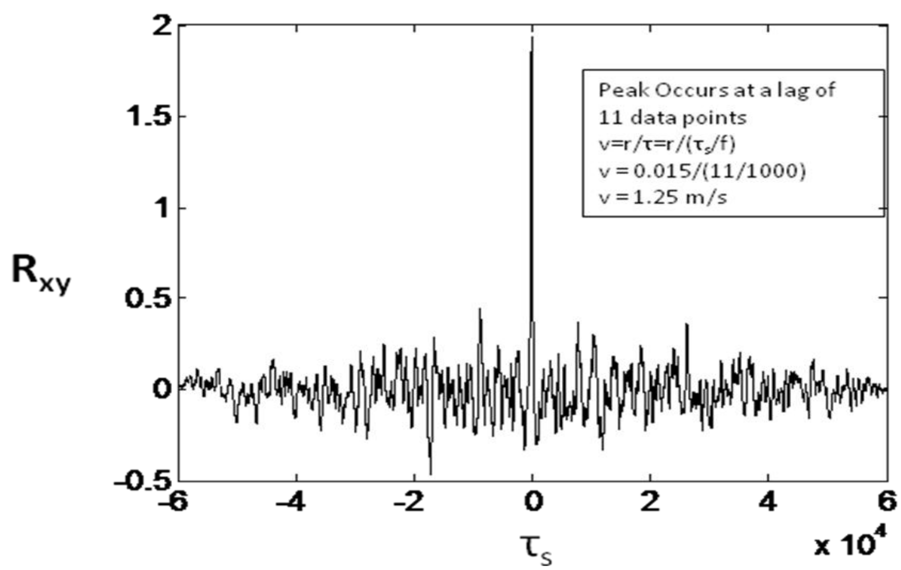

Figure 4b: Graph of cross correlation function R_{xy} vs. lag for data taken at velocity 1.1 m/s sampling rate of 1000 Hz, and spacing of 15 mm. Peak occurs at a τ_s of 11 samples when corresponds to a velocity of 1.25 m/s.

Figure 5 shows the comparison of the measurements of the CCV at different sampling distances with respect to the hot wire anemometer. The velocity and temperature of the flow are maintained constant at 1.1 m/s and 313 Kelvin respectively, and the sampling rate is fixed at 1000 Hz. Each data point in Figure 5 is an average of 4 experimental runs. The gray band drawn horizontally denotes the velocity measured by the hot wire anemometer with an error band of ± 15% (after each experimental run, the hot wire anemometer was tested for its ability to correct for temperature and showed a 20-30% reduction in measured speed between 295 K - 315 K which accounts for majority of the error). As shown in Figure 5, increased precision in the CCV measurement is observed as the separation between the two thermocouples increases from 5 mm to 15 mm. At this spacing all four velocity measurements were calculated to be the same. The smaller spacing's (<15 mm) are more susceptible to the small errors in the measurement where of a single lag can lead to significant error. As the spacing distance is further increased (>15 mm), the precision of the CCV measurement once again declines. The larger spacing cause the turbulent eddies to weaken (condition of frozen eddy not satisfied) and thus cause significant measurement error. Figure 6 shows the velocity measurements at a spacing of 15 mm for sampling frequencies of 1000, 2000, and 3000 Hz. It is clear that the CCV technique works well given this frequency range. Further experimentation is planned to test the measurement technique especially at lower frequencies.

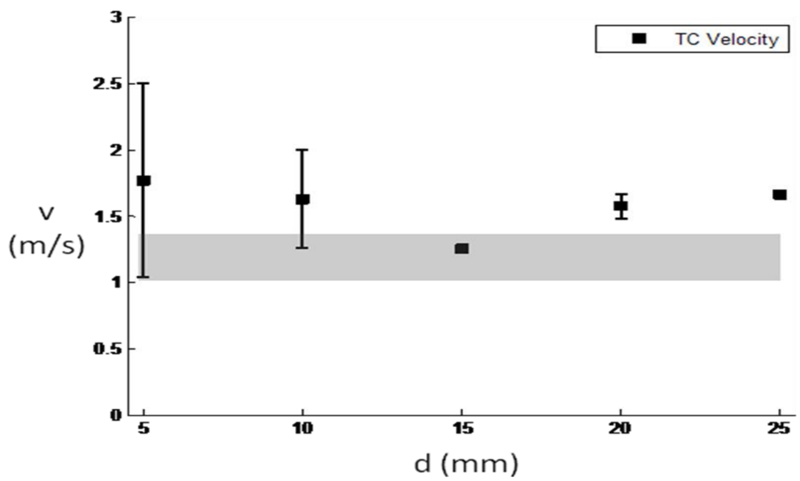

Figure 5: CCV velocity measurement and hot wire anemometer vs. separation distance for a sampling rate of 1000 Hz and a flow speed of 1.1 m/sThe gray band indicates the measurement from the hot wire anemometer including the instrument error.

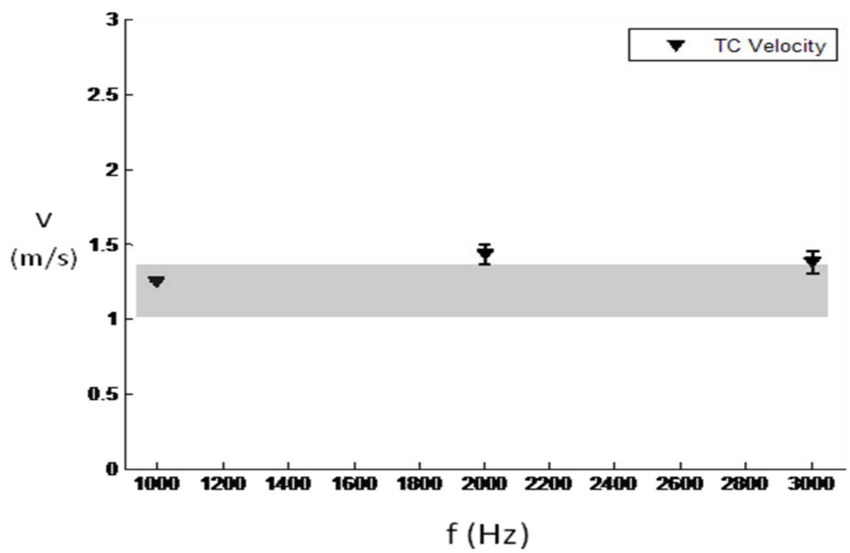

Figure 6:Temperature cross correlation velocimetry and hot wire anemometer vs. sampling rate at separation distance of 15 mm. Technique works well for sampling rates over 1000 Hz. The gray band indicates the measurement from the hot wire anemometer including the instrument error.

Conclusion:

For a turbulent flow at 1.1 m/s this study has shown that the most accurate and precise velocity measurement predicted by the CCV technique is nominally found at a spacing of 15 mm. Future work includes obtaining a relationship between eddy size and optimum thermocouple spacing distance using flow visualization techniques. In addition, the height above the axisymmetric jet as well as the distance along the radius of the jet will be varied to find an overall flow profile. Once this is accomplished, measurement of entrainment velocity of pool fires of varying sizes is planned. The frequencies covered in this study have shown little effect on either accuracy or precision. Future work to obtain the minimum viable frequency is planned.

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