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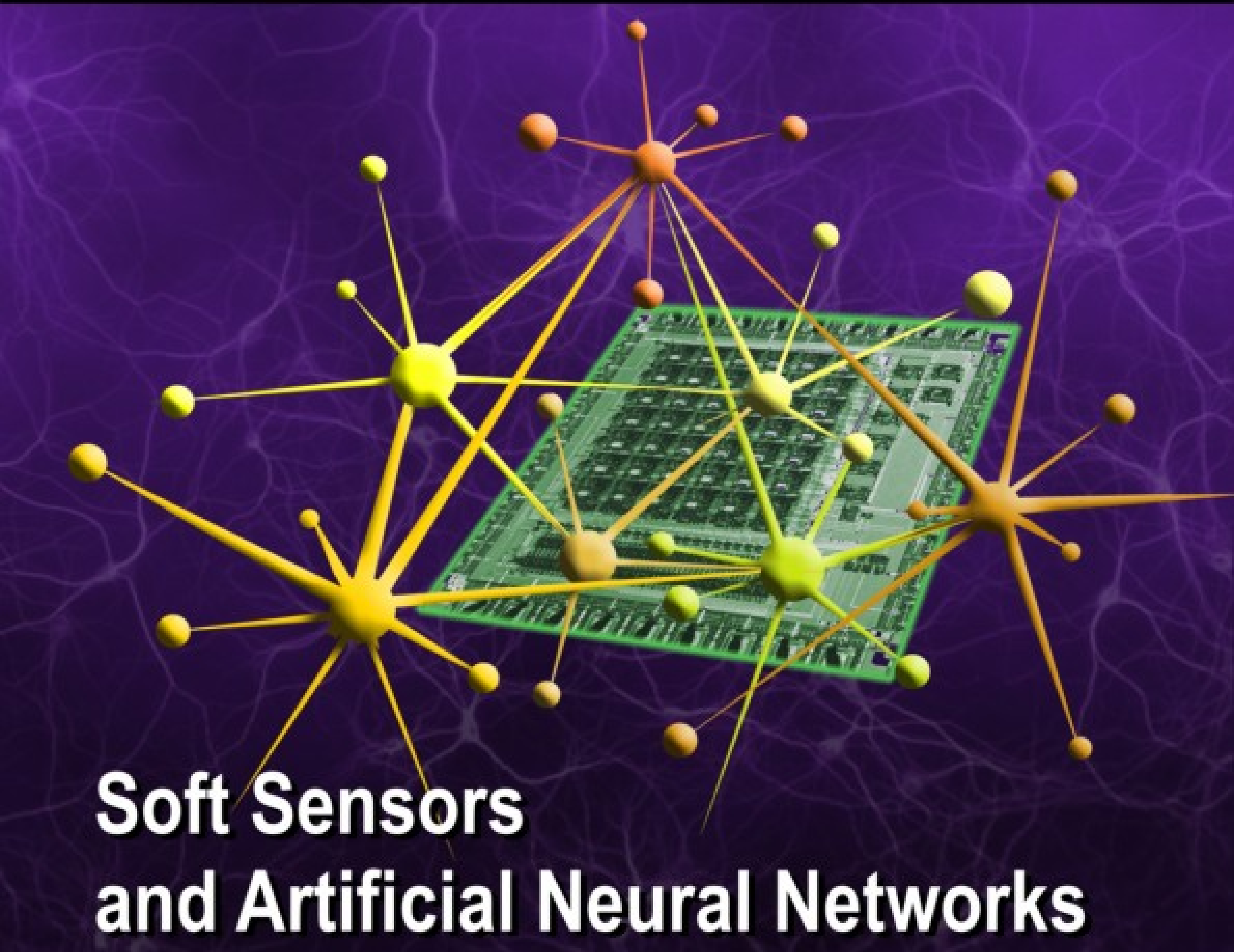

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Modeling of the Response of a Hot-Wire Anemometer with Neural Nets under Various Air Densities

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Abstract: The sensors, which use the convective heat transfer at hot wires in order to measure the flow rate of gases, are well known. Hot-Wire Anemometry (HWA), which is operated in either constant-current mode or in constant temperature mode, represents the most popular methods to measure the velocity and the flow rate of the fluid flow. Generally, the hot-wire sensors are calibrated against the flow velocity under atmospheric pressure conditions. To calibrate hot-wire sensors under different air densities; a special calibration test rig is needed. In the present paper, calibrations are shown to yield the same hot-wire response curves for density locations in the range of 1 to 7 kg/m3 and its usable mass flow rate range (ρU) is 0.1 to 25 kg/m^{2}s.

Also, a neural network has been trained with the output data for the hot-wire sensor and tested on our measurements. It was observed that the quality of the results depends on the number of hidden neurons. The predicted values are close to the real ones which indicate the neural net model gives a good approximation for the calibration curves of the hot-wire anemometer under different flow densities. The hot-wire sensor that used in the present study has 5 μm diameter and 1.25 mm length so its aspect ratio is 250. *Copyright © 2007 IFSA.*

Keywords: Neural Networks, Modeling, Hot-Wire Anemometer.

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1. Introduction

In fluid mechanics, there are many engineering applications which require air velocity to be measured. Sensors which use the convective heat transfer from a heated wire placed in a fluid flow in order to measure the flow rate of gases are well known. Hot-wire and hot-film anemometers are typical representatives of this subclass of thermal flow sensors, e.g. [1-3]. They are usually operated under constant temperature (CTA) or constant current (CCA) conditions and are also employed for flow-rate measurements in a wide range of applications, e.g. [4-7]. The type of constant temperature operation is widely used these days for the measurement of the rapid velocity fluctuations due to its simple compensation circuits. It works based on the fact that the probe's resistance will be proportional to the temperature of the hot wire. There are major advantages in maintaining the hot wire at a constant operational temperature and thereby at constant hot resistance, since the thermal inertia of the sensor element is automatically adjusted when the flow conditions vary. This mode is achieved by incorporating a feedback differential amplifier into the HWA circuit to obtain a rapid variation in the heating current to compensate for instantaneous changes in the flow velocity.

In hot-wire anemometer, the sensor consists of a very fine metallic element, whose diameter is typically about 5 μm, supported by two prongs at the end of a slender probe body. The wire is heated by an electric current and simultaneously cooled by convective heat transfer induced by the lower temperature incident flow. The wire will experience heat losses by convection, conduction, and radiation depending on the flow conditions. The conduction and radiation have a small effect on the heat losses for the wire but the major effect is for the convection. The convection heat losses are a function of the flow conditions. Any change in the flow velocity will affect the coefficient of heat transfer and consequently the temperature of the wire, which also affects the wire resistance, e.g. Al-Salaymeh [8].

Modelling using artificial neural networks (ANN's) is a powerful tool for approximating nonlinear systems that are complex and difficult to identify based on the physical phenomena. System identification with neural networks has been applied to highly nonlinear industrial processes [9-15]. The availability of an input–output ANN model for a complex process allows the prediction of the system behavior. In this paper, we study the feasibility of approximating of the calibration data of a hot-wire anemometer under different air densities with ANN's.

2. Previous Work

Hot wire anemometers have been used since 19th century, when experimentalists in fluid mechanics built their own rudimentary constant current anemometers. Because no commercial equipment was available, all improvements were made by the scientists themselves. The exact date of the first report of the hot-wire anemometer is difficult to state, but it seems to go back to the beginning of the last century. Indeed, according to King [16], preliminary experiments on the use of a platinum wire heated by an electric current for the measurement of wind velocity were carried out by Shakespear, at Birmingham, as early as 1902; they were discontinued for lack of facilities for the erection of a suitable whirling table for calibration of the wires. The available publications concerning early electrical anemometry therefore appear to be, first, Kennelly et al. [17] and then, independently, Morris [18] and Gerdien [19]. The contribution of King [16, 20] was important both for the design of hot-wire anemometers and for the theory of the convection of heat from cylinders immersed in a stream of fluid.

Measurements of heat losses from long cylinders located in free flows have been extensively carried out by various researchers, e.g. Norberg [21], since the 1914 work of King [20]. Heat-transfer laws for infinitely long cylinders are often used to predict the behaviour of heated wires and films, the length-to-diameter ratio being almost always large enough for this to be a good local approximation. These laws are usually expressed in non-dimensional form by giving the Nusselt number as a function of Reynolds number. One of the first heat-transfer laws was due to, and bears the name, of King [20]. King presented his results in terms of heat transfer coefficients, one year before Nusselt [22] suggested a more general presentation, using a non-dimensional number, which is nowadays referred to by his name, to correlate heat-transfer data. Subsequent investigators presented their measurements in the form of Nu (Re) diagrams, e.g. Collis and Williams [23].

The evolution in the development of hot-wire probes had begun in the second half of the 20th century when electric amplification and shaping networks were added, and the constant current anemometer becomes a sophisticated, high frequency response research instrument.

The appearance of commercial constant current anemometers, and later of commercial constant temperature anemometers, coincides with a major growth in popularity of these instruments. Today the hot wire anemometer is used in research laboratories through out the world. There are many studies in the literature which have been contributed in development the hot wire anemometer and they are considered as excellent references. Some examples of the most convenient researches are Comte-Bellot [24], Blackwelder [25] and Fingerson and Freymuth [26].

3. Theoretical Background

The topic of hot wire anemometry (HWA) has been thoroughly looked upon aeronautic, chemical and mechanical engineers for the last century. HWA is based on convective heat transfer from a heated wire or film element placed in a fluid flow. The heat is generated inside the hot wire due to the wire resistance when the electrical current passes through it. The heat transfer from a heated wire placed in fluid flow depends on the properties of the ambient fluid (e.g. density, viscosity, thermal conductivity and specific heat) and parameters of the flow (e.g. velocity vector, fluid temperature and pressure).

Fig. 1 shows a schematic diagram of a hot wire anemometer. The sensor of the typical hot-wire probe is a wire, usually made of tungsten or platinum, about 1.25 mm long and 5 µm in diameter. The sensor is attached between the tips of two support needles by arc welding or soldering, and is electrically heated. The needles are usually made of materials that have low thermal conductivity. Its convection cooled by the fluid passing over it, and this cooling effect is a measure of the fluid velocity. The probe body is usually made of epoxy of ceramic material of fabricated from a metal tube potted with epoxy. An electrical connecter is often located at the other end of the probe body to allow easy removal and replacement of the probe. The contacts of the connector are sometimes plated with gold to reduce resistance, and the connector is usually designed to be watertight. The wire was operated under constant temperature and a feedback electronic circuit was used to modify the electrical current.

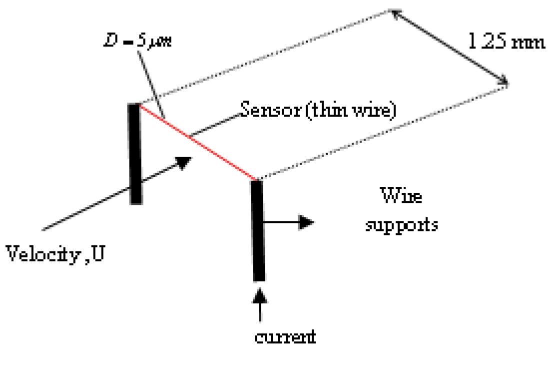

Fig. 1. A schematic diagram of the hot wire anemometer.

The heat-transfer characteristics of hot-wire sensors are reasonably well understood. The operation of the hot-wire anemometer is based on the assumption of uniform heat transfer over the length of the wire, and therefore the aspect ratio is selected to be always larger than 250. The choice of minimum length-to-diameter ratio is based on previous work, e.g. [5], which showed experimentally that the end conduction losses have a negligible effect on the sensor temperature profile for sensors with a length-to-diameter ratio greater than 250.

Hot-wire anemometry is a measuring technique that is widely applied in fluid mechanics to provide experimental data of local mean velocities. The accuracy of such measurements strongly depends on the accuracy of the calibration of the applied hot-wire sensor. Hence, good and reliable calibrations are essential to study flows by means of hot-wire anemometry. Established procedures are available to yield such calibrations for measurements of flows with constant fluid properties. It is common practice to calibrate the applied hot-wire for these fluid properties to yield experimental data that follow closely the theoretically deducible law, e.g. Brunn [1]:

$$\frac{I^2 R_w}{R_w - R_g} = \frac{V^2}{R_w\left(R_w - R_g\right)} = A + BU^n \quad , \tag{1}$$

where I is the electrical current through the wire, R_w is the resistance of the hot-wire and R_g the resistance of the wire at gas temperature, V^2 is the square of the out-put of the hot-wire anemometer bridge, A and B are constants, U is the calibration velocity and n is an exponent. Hence, if the wire temperature and the fluid temperature are kept constant, i.e. R_w = const. and R_g = const., the above hot-wire response relationship results in a calibration law for the velocity response of the wire. The available physical understanding of hot-wire anemometry suggests, that the heat transfer from hot-wires should follow a relationship, e.g. King [16]:

$$V^2 = A^* + B^* \sqrt{\mathrm{Re}} \quad , \tag{2}$$

where Re is the Reynolds number ($\mathrm{Re} = Ud/\nu$), ρ is the fluid density, and ν is the kinematic viscosity, A^* and B^* are new constants. The relation that was used for describing the cooling of the wire by a gas flow was that given by King [16], derived theoretically on the assumptions of potential flow around the wire:

$$I^2 R_w = kl\left(T_w - T_g\right)\left(1 + \sqrt{2\pi \frac{\rho_g c_p dU}{k}}\right) , \tag{3}$$

where k is the heat conductivity of gas, T_w is the wire temperature, T_g is the gas temperature, ρ_g is the gas density, c_p is the heat capacitance of the gas, and d is the wire diameter.

4. Neural Net Modelling

Artificial neural networks were originally inspired as being models of human nervous system. They have been shown to exhibit many abilities, such as learning, generalization, and abstraction [28]. Useful information and theory about ANN's can be found in [29]. These networks are used as models for processes that have input-output data available. The input-output data allows the neural network to be trained such that the error between the real output and the estimated (neural net) output is minimized. The model is then used for different purposes among which are estimation and control.

The neural net structure is shown in Fig. 2. The inputs feed forward through a hidden layer to the outputs. The hidden layer contains processing units called nodes or neurons. Each neuron is described by a nonlinear sigmoid function. The inputs are linked to the hidden layer which is in turn linked to the outputs. Each interconnection is associated with a multiplicative parameter called weight. Note that the feed-forward neural net of Fig. 2 has only one hidden layer and this is the case that we are going to consider. A number of results have been published showing that a feed-forward network with only a single hidden layer can well approximate a continuous function [30, 31]. In practice, most of the physical processes are continuous. However, the results of this paper can easily be extended to include multi layer neural networks.

An artificial neural net mathematical model that represents the structure shown in Fig. 2 is written as

$$Y = f(U) = W_o * \tanh(W_i * U + B_i) + B_o \, , \tag{4}$$

where, Y is a column vector which contains the q outputs of the process, U is a column vector that contains the p inputs of the process, W_o is a matrix of size qxn that contains the weights of the neural net model from the hidden layer to the outputs with n being the number of neurons in the hidden layer, W_i is a matrix of size nxp that contains the weights of the neural net model from the inputs to the hidden layer, B_i (not shown in Fig. 2) is a column vector of size n that contains the biases from the inputs to the hidden layer and B_o (not shown in Fig. 2) is a column vector of size q which contains the biases from the hidden layer to the outputs.

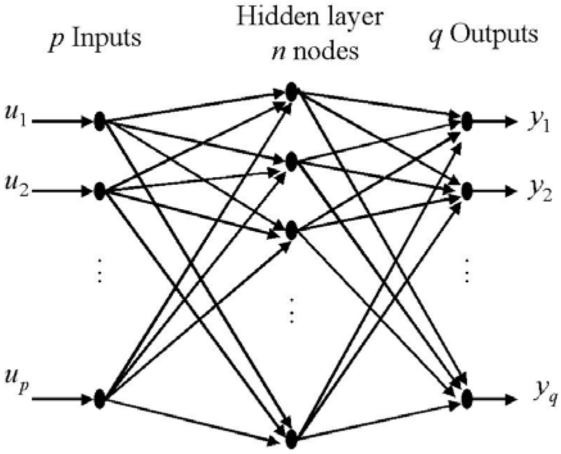

Fig. 2. Neural net structure.

Each input u_j, j=1, 2, ... , p has lower and upper bounds, Lb_j and Ub_j, respectively. These bounds are calculated from the available input-output data. Lb_j is the minimum value of the j^{th} input over the given input data whereas Ub_j is the maximum value of the jth input over the same data. If all the inputs lie within their lower and upper bounds then the estimated output by the ANN should lie within the given output data range. The output bounds are dictated by the ANN and the input bounds.

The weights and biases of the ANN are determined by training with the historical input-output data. Back propagation is an example of a training algorithm.

The available data is divided into two parts: one part is used for training the net whereas the other usually smaller part is used to test the performance of the ANN. The number of hidden neurons n affects the performance of the neural net over the training and test sets of data. More neurons make the fitting of data more accurate over the training region. It is more important to check the generalization performance of the model over the test set of data since it was not used to calculate the parameters of the model. The number of nodes is usually chosen by trying different values and selecting the one that gives best results over both the training and test regions.

5. Experimental Results

In the present investigation, the air velocities measured were in the range 0.1-25 m/s. Wire voltages were calibrated against air flow velocities which was determined by a special mass flow control unit, to an inaccuracy of 1% from the reading. Overall temperature variation of the air was typically less than ±0.5°C during the course of the entire experiments at room temperature.

5.1. Hot Wire Calibration Test Rig

Experimental investigations were performed to quantify the response of the hot-wire anemometer at various flow densities. For this purpose special experimental test rigs have been designed and built at the Institute of Fluid Mechanics of the Friedrich-Alexander-University of Erlangen-Nürnberg to carry out hot-wire calibration at a wide range of mass flow rates. The setup consists of a mass flow control unit, a pressurized container, a cylinder chamber with a nozzle, a relief valve, temperature and pressure sensors in addition to the hot-wire anemometry as shown in Fig. 3. More details about the calibration setup are given in Durst et al. [27]. The mass flow rate control unit (Luftikus) was used to set up a predefined mass flow rates and to control them. The principle of this device depends on allowing the air to flow through a convergent-divergent nozzle which can act as a limiting valve, allowing only a certain maximum mass flow for a given set of stagnation conditions. The throat area of the nozzle has variable cross-sections so that a definite area will be required for a given mass flow. When the ratio of the back-pressure to the stagnation pressure reaches 0.528, i.e. Mach number equal to one (Ma = 1), then a sonic condition is reached at the nozzle throat area and the flow properties here are termed critical properties. A further decrease in the pressure ratio (Ma > 1) does not affect the flow in the convergent nozzle. The mass flow consequently cannot be increased and the nozzle is now considered to be operating in the choked condition.

The facility is working with air supplied by the source through a well designed pressurized container. The mean mass flow rate is measured at pipe center using a hot-wire anemometer which is connected to 16-bit DAQ card. The hot-wire sensor was fixed in the mouth of the exit nozzle where the actual investigations of the flow were carried out. Two perforated plates were designed and arranged properly in the cylinder chamber and separated by 10-cm distance from each other to minimize any flow swirling and other lateral velocities and to reduce the turbulence level at the position of hot-wire anemometer. Hot-wire anemometry has been used for getting mass flow rate for each investigated density covering the whole range of interesting. A pressure transducer was used for measuring the pressure with an accuracy of ±0.2% of the actual reading. For temperature measurements, two thermocouples (type K) were used at all times during measurements within accuracy range of ±0.1 °C. The estimated uncertainty in the measurement of mass flow rate is less than ±1%. The calibration measurements were performed in the density range of 1-7.

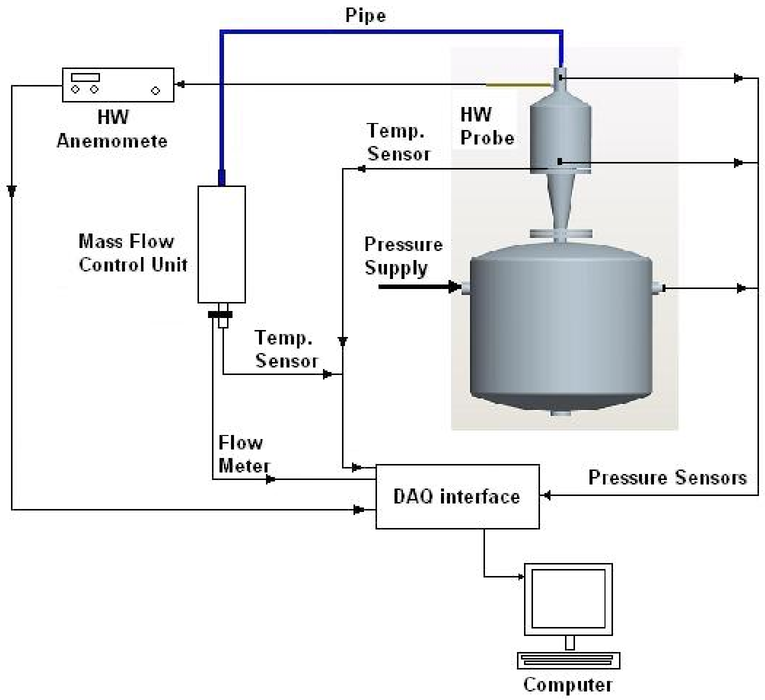

Fig. 3. Schematic diagram of the experimental setup showing the mass flow control unit with the pressurized container, the temperature, pressure, velocity measuring equipment, and measuring test section.

Measurements have been carried out to calibrate the hot-wire anemometer at different values of (ρU) in the range of 0.1 to 25 kg/m²s by using a mass flow rate control unit. The measurements were performed using a DANTEC 55 P61 single straight constant-temperature hot wire probe. The probe was normal one, equipped with a wire of 5 µm diameter and an active wire length of 1.25 mm, providing an aspect ratio, l/d, of 250. Hence the wire had sufficiently large aspect ratios to suggest a negligible influence of the prongs on the actual velocity measurement. All calibrations and measurements were performed with an 80% overheat ratio. To carry out measurements, the hot-wire anemometer was installed directly at the centerline of the pipe entrance and just at the nozzle exit where a uniform and well-defined flow field existed. In addition, the air temperature inside the pipe was measured at all times during measurements within accuracy range of ± 0.1 °C. The ambient conditions as well as the temperature inside the container were monitored before and during each test run using thermocouple sensor. All electronic equipments were connected to an A/D converter board from National Instruments with 16-bit resolution and 8 input channels. In addition, a computer-based programming system was used for acquiring and processing all the measured data.

Hot wire output is a temperature dependent and therefore a correction for temperature drift is necessary if the temperature of the working fluid can not be kept constant during calibrations and measurements. Different methods are available in the literature to deal with the problem of air temperature effect on hot-wire output. For small temperature changes, i.e. approximately ±5 °C, Bearman [32] gave a good treatment of the problem and he introduced the following expression to correct hot-wire output for the temperature drift:

$$V_{corr.} \cong V_{meas.}\left(1-\frac{\varepsilon}{2\sigma}\right), \tag{5}$$

where $\varepsilon = (T_{ref.} - T_{meas.})/T_{ref.}$ and $\sigma = (T_{wire} - T_{ref})$, $T_{ref.}$ is a reference temperature, T_{meas} is the measurement temperature, and T_{wire} is the wire temperature. In the present study an instantaneous correction for the hot-wire output was carried out in case of any temperature drift existed utilizing the relationship of Bearman [32].

5.2. Calibration Results

The present investigations aimed at calibrating the hot wire anemometry against (ρU) values. The setup that is described in Fig.3 was employed to calibrate the wire for a different pressure values. The pressure inside the vessel was controlled by means of a pressure reducer that was installed on the tank inlet. The total rate of heat transfer from the sensor is a function of the fluid velocity, the temperature difference between the mean sensor temperature and the fluid, the fluid properties and the probe properties and geometry. When used as an anemometer, one attempts to hold all variables constant except the velocity. However, if any of the other properties change, the heat transfer rate, and thus the output of the device, will change. The calibration curves of the hot-wire anemometer are shown in Figs. 4 and 5 as an output voltage against the flow velocity or the volume flow rate for different air pressures. It is clear from Figs. 4 and 5 that the response of the hot-wire anemometer is proportional to the flow pressure or density and there are different outputs for the same flow velocity but different air pressures. To the authors' knowledge, this is the first comprehensive experimental study of the calibration of HWA taking into account not only the flow velocity and temperature, but also the flow pressure and density. Most of the previous work in this field has been concentrated on the calibration of HWA at ambient conditions and little effort has been devoted to high pressure flows. This investigation was achieved thanks to the special experimental setup that designed and built at the institute of Fluid Mechanics of Erlangen University in Germany.

Durst et al. [27] suggested that the hot-wire response is a function of the local mass flow rate (ρU) rather than the local velocity U. This has been stressed in the literature but convincing data to proof V^2 (ρU) over a wide range of density variations are not available.

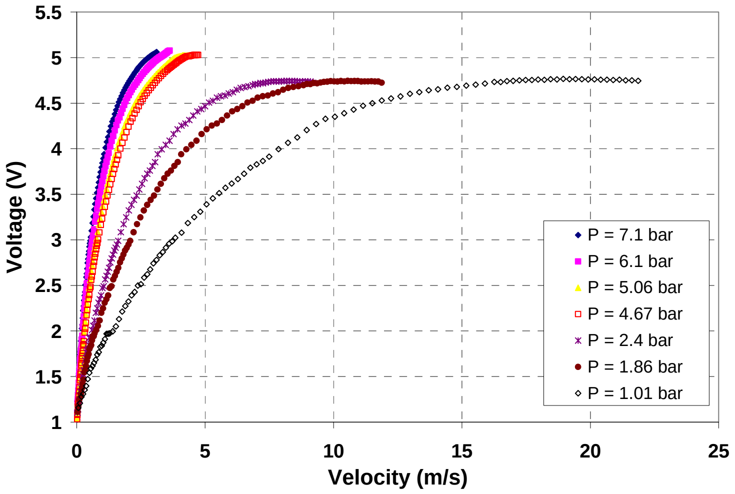

Fig. 4. The response of the hot wire anemometry as a function of the flow velocity (U) for an input pressure values between 1 and 7 bar.

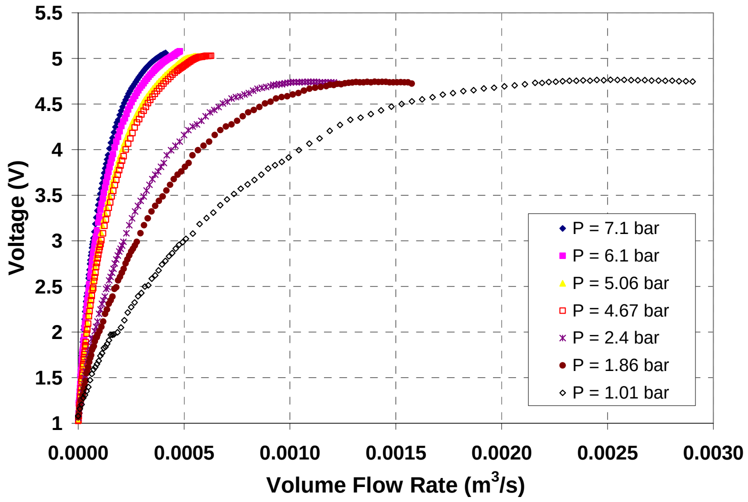

Fig. 5. The response of the hot wire anemometry as a function of the volume flow rate (UA) for an input pressure values between 1 and 7 bar.

Fig. 6 shows the response of the HWA as a function of the mass flow rate per unit area (ρU) for different air pressures. It is clear from Fig. 6 that all the calibrations for different flow densities have a common calibration curve. This figure indicates that the hot wire anemometry response is a function of (ρU) rather than the local velocity. It is clear that when (ρU) is increased the convection heat transfer from the wire is increased which cause the probe output to increase also.

A comparison between the response of the hot-wire anemometry as a function of the mass flow rates at different air densities or pressure is presented in Fig. 7. This figure shows the dependency of the wire output on the mass flow rate for pressure values of 1.01, 1.86, 2.4, 4.67, 5.06, 6.1 and 7.1 bar and it is obvious that the calibration curves for the studied pressure values are identical. It is clear from Figs. 6 and 7 that the wire output depends strongly on (ρU) values. The universal calibration curve for a wide range of vessel pressure which is shown in Fig. 6 or Fig. 7 supports the theoretical findings of King. Furthermore, a very good agreement was observed between the calibration curves that were obtained for both high and low pressure ranges. The error in the wire output value is estimated to be about 1%.

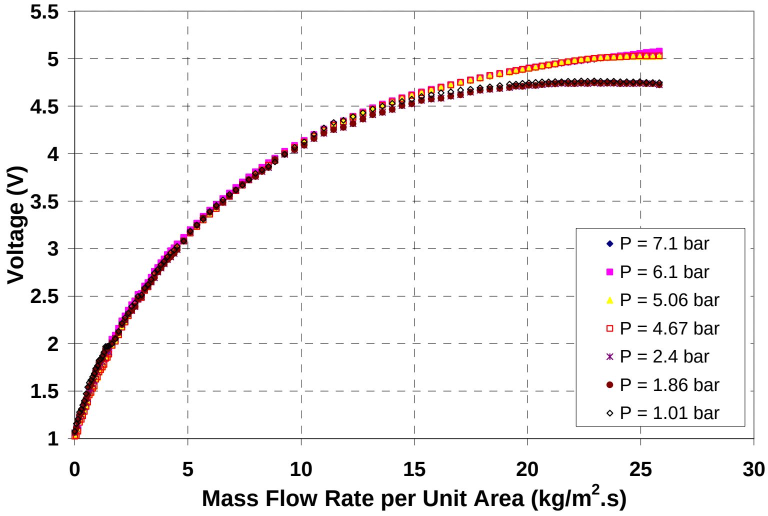

Fig. 6. A comparison between the response of the HWA for vessel pressure between 1 and 7.1 bar over a wide range of (ρU).

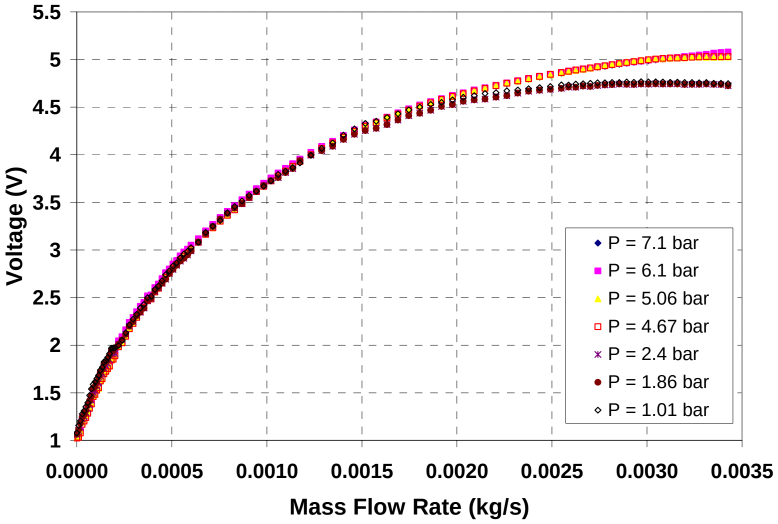

Fig. 7. The response of the HWA as a function of the mass flow rate (ρUA) for an input pressure values between 1 and 7.1 bar.

6. Response Approximation of HWA

Neural net modelling is applied in this paper to the calibration curve data of the hot-wire anemometer at different air pressures. Treating the data as an input–output system allows us to approximate it with a neural net model. We develop two neural net models for the hot-wire anemometer. In the first (mass flow rate) model, the inputs of the system are the mass flow rate and pressure, and the output of the system is flow measurement voltage. On the other hand, the inputs of the second (volume flow rate) model are the volume flow rate and pressure, and the output of the system is flow measurement voltage. The available input–output data is divided into two parts. One part is used to train the neural net, whereas the other part is used to test it. The data includes 686 patterns for training and 49 patterns for testing. The training was done with the software package Matlab. We ran experiments for different numbers of hidden neurons. It was observed that the quality of the results depends on the number of hidden neurons. The results are plotted in Figs. 8 and 9 for the first and second ANN models, respectively. We choose the neural net with five hidden neurons for the first model, whereas the neural net with four hidden neurons is selected for the second model. These are the smallest number of hidden neurons with acceptable least square errors over the training and test regions. It is advantageous to have an ANN with small number of hidden nodes since its structure will be small and the number of its parameters will also be small. The real and predicted (ANN) values of flow voltage over the whole (test and training) region are plotted in Figs. 10 and 11 as functions of mass and volume flow rate, respectively. The corresponding results over the test region are shown in Figs. 12 and 13 where the x-axis is the index of the data. Note that the predicted values are close to the real ones which indicates that the neural net model gives a good approximation for the performance of the hot-wire sensor at different operating pressures as a function of the volume flow rate. If the flow rate is replaced by the flow velocity then the results will be as shown in Figs. 14 and 15 for the mass (first) and volume (second) flow rate models, respectively.

It is worth to mention that when we trained the ANN a transformation was applied to the input and output. This transformation is basically mapping the input and output values to the interval [0,1] and is called normalization. The normalization was needed due the scale difference between the inputs and the output. The following transformation is applied to the inputs and output:

$$x_n = \frac{x - x_{\min}}{x_{\max} - x_{\min}}, \tag{6}$$

where x_n is the normalized value, x the original value, $x_{\min}$ the minimum value over the given data and $x_{\max}$ is the maximum value over the same data. The normalized input–output data is passed to the training algorithm in the Matlab software package. The corresponding numerical values of the net weights and biases as given in Eq. (4) are found as

$$W_i = \begin{bmatrix} 5.67 & -3.74 \\ 6.48 & 4.95 \\ 2.20 & 5.38 \\ 4.05 & -5.57 \\ 1.92 & -0.04 \end{bmatrix}, B_i = \begin{bmatrix} -4.94 \\ -5.46 \\ -4.20 \\ -1.69 \\ 1.37 \end{bmatrix}, B_o = -6.75 \text{ and}$$

$$W_o = \begin{bmatrix} -0.01 & -0.02 & 0.03 & -0.00 & 7.74 \end{bmatrix}.$$

for the first ANN model and they are equal to

$$W_i = \begin{bmatrix} -13.64 & 0.46 \\ 18.76 & -3.19 \\ -7.18 & -30.55 \\ -7.97 & -2.18 \end{bmatrix}, B_i = \begin{bmatrix} -2.42 \\ -3.84 \\ 4.10 \\ 1.65 \end{bmatrix},$$

$$W_o = \begin{bmatrix} -21.49 & -0.06 & -0.05 & -0.33 \end{bmatrix} \text{and } B_o = -20.90.$$

for the second ANN model.

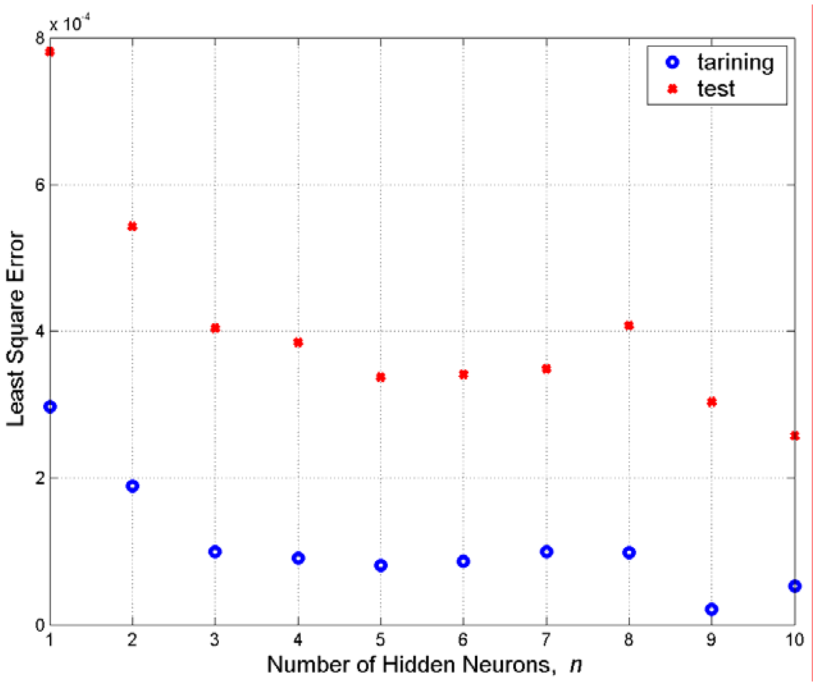

Fig. 8. Least square error associated with training the ANN for flow voltage as a function of mass flow rate and pressure.

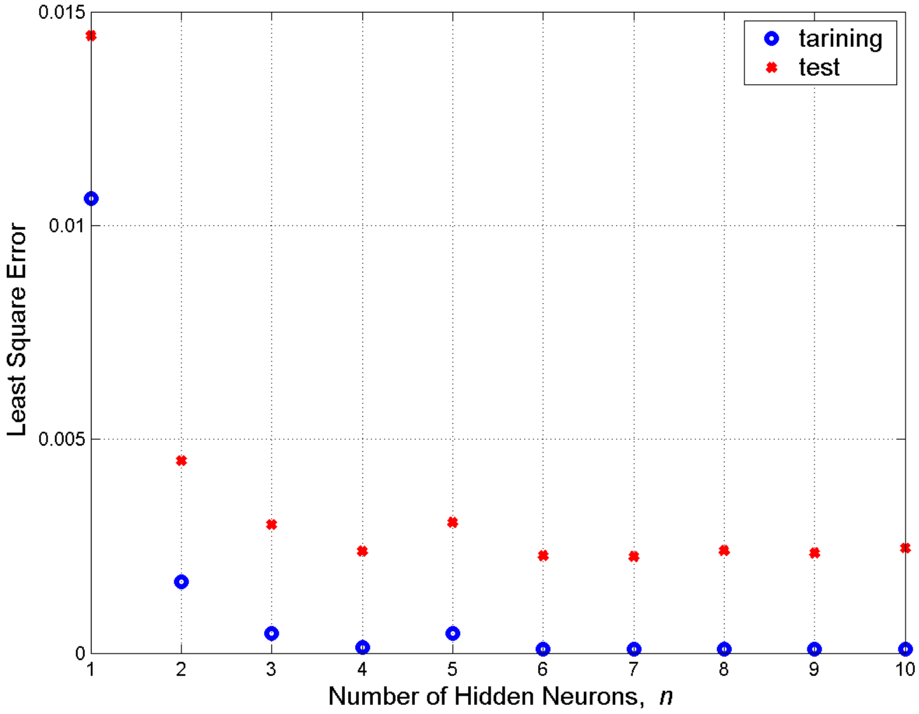

Fig. 9. Least square error associated with training the ANN for flow voltage as a function of volume flow rate and pressure.

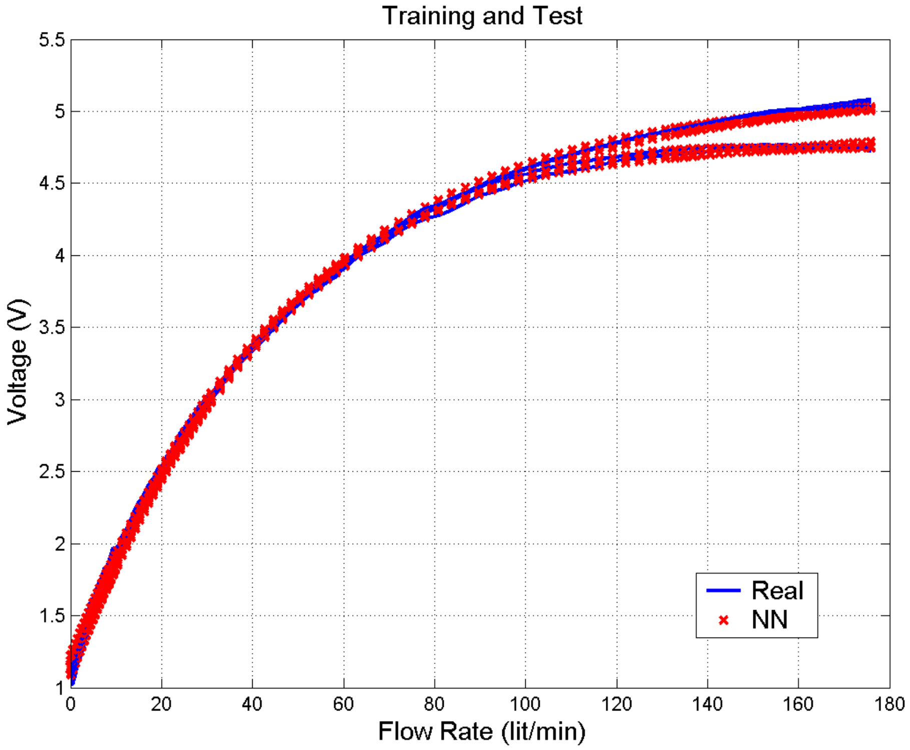

Fig. 10. Training and test neural net results for the mass flow rate model.

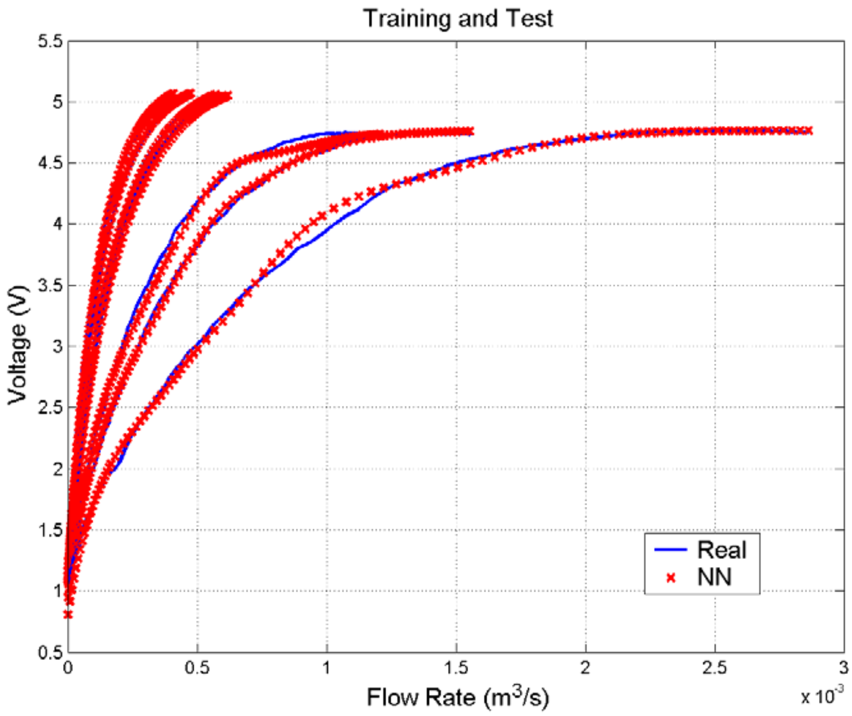

Fig. 11. Training and test neural net results for the volume flow rate model. Note that the different curves have different pressure values ranging from 1 to 7 bar.

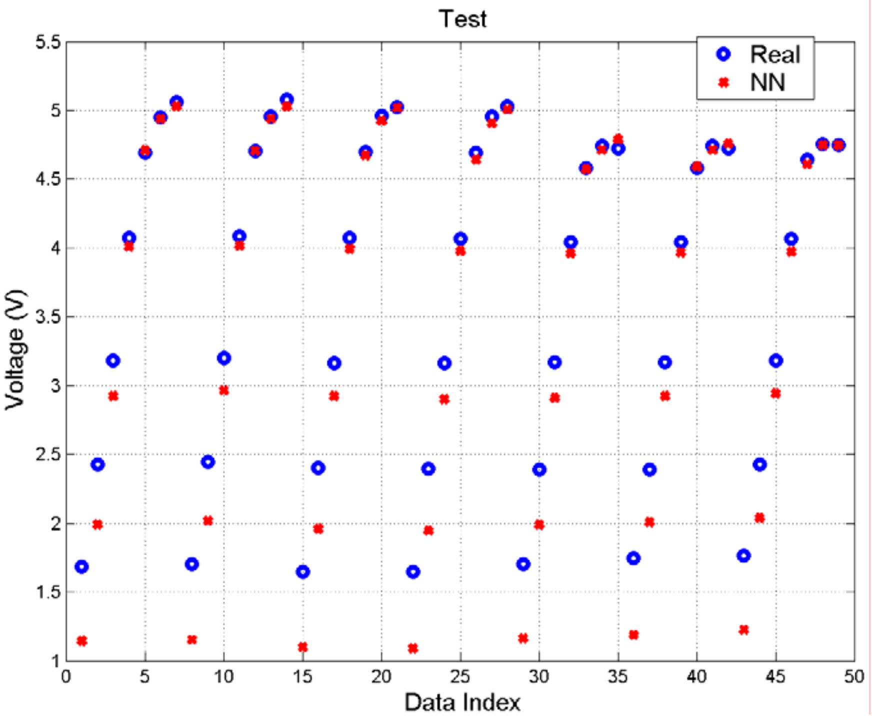

Fig. 12. Test neural net results for the mass flow rate model.

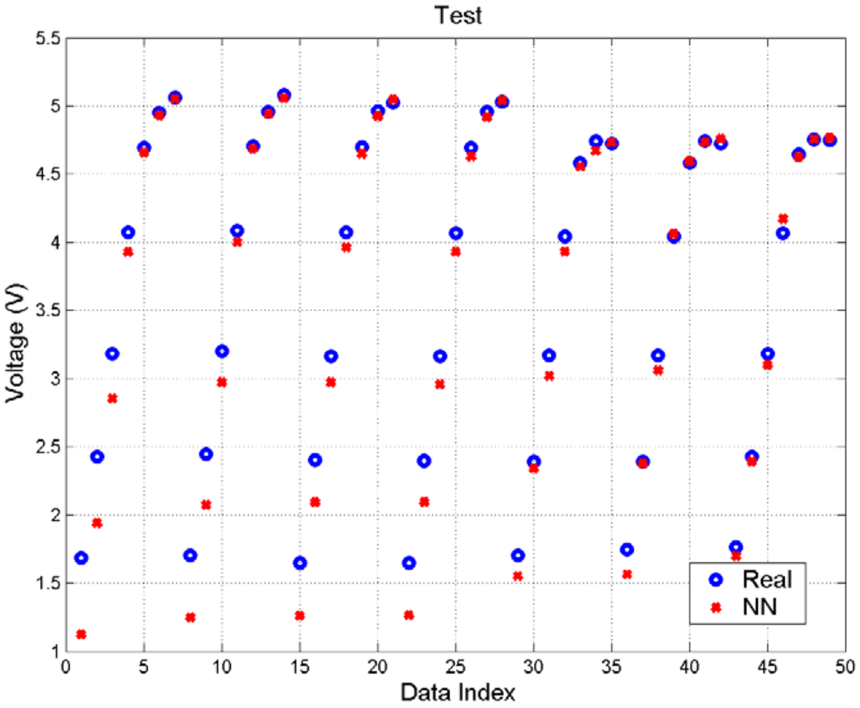

Fig. 13. Test neural net results for the volume flow rate model.

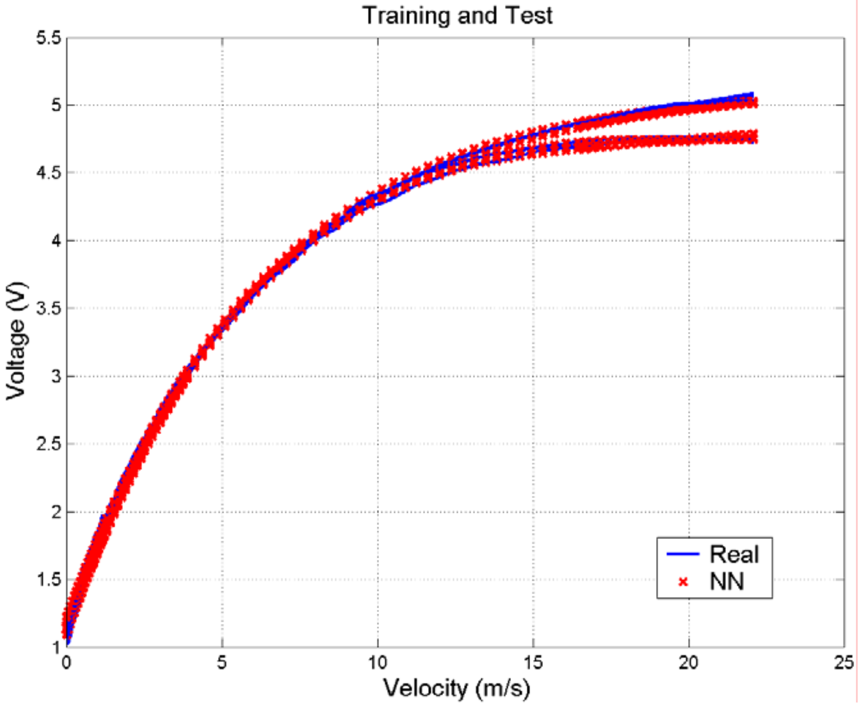

Fig. 14. Training and test neural net results for the mass flow rate model with flow rate replaced by velocity.

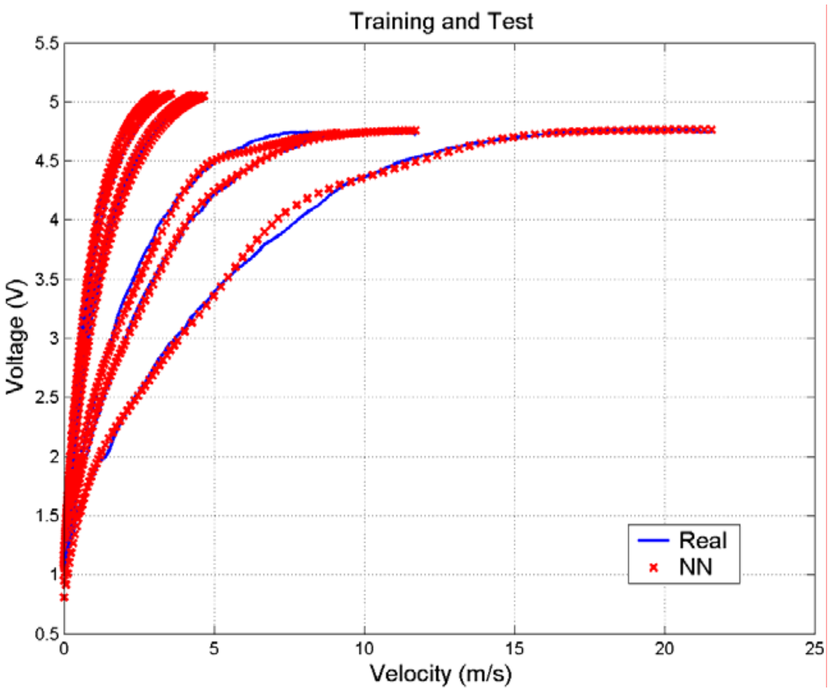

Fig. 15. Training and test neural net results for the volume flow rate model with flow rate replaced by velocity.

7. Conclusion

Hot-wire sensors have many uses which include domestic and industrial purposes. The hot wire probe is a very delicate instrument implying that improper handling will cause easy breakage of the probe. The response of the hot wire is affected by the variations of the flow conditions and consequently the changes in the heat transfer rates. The experimental investigations carried out in this study are related to the calibration of the hot wire anemometry at variable air densities by using a special flow controller unit. The experiments were carried out with a wide range of mass flow rate from 0.1 to 25 kg/m^2.s. The present paper has mainly discussed the effect of flow pressure on the response of the hot wire anemometer.

An artificial neural network (ANN) model for the performance of the hot-wire sensor under different operating conditions such as pressure has been carried out. The ANN approximates the experimental data well and has a reasonable number of parameters.

No one can claim that in the hot-wire anemometer, a universal calibration curve can be obtained. We emphasize that individual calibration of probes is necessary for the highest accuracy: wire diameters in the micron range cannot be precisely controlled, nor can wire and prong resistance.

Acknowledgment

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