Design and Simulation of MEMS Anemometer

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***Abstract*— Wind speed measurement is a very important factor in various fields such as aeronautics, meteorology and farming. The conventional wind sensor comprises of small mechanical apparatus such as propeller and cup anemometers, or consists of thermal element such as hot wire anemometers, or has acoustic part such as acoustic radar. This paper concentrates on the design and simulation of a MEMS wind speed sensor (Anemometer) which is sensitive to low wind speed. The sensor that is based on the thermal anemometer principle was designed using COMSOL Multiphysics and subsequently simulating its working, performing a thorough study of the parameters involved and propose inroads into possible improvements in design and applications.**

***Index Terms*—Microelectromechanical systems, anemometer, calorific meter, conjugate heat trasfer.** *(key words)*

I. INTRODUCTION

An anemometer or wind-meter is a device used for measuring wind speed, and is a common weather station instrument. The term is used to describe any air speed measurement instrument used in meteorology or aerodynamics. The Hot-Wire Anemometer is the most well-known thermal anemometer, and measures a fluid velocity by noting the heat convected away by the fluid. The core of the anemometer is an exposed hot wire either heated up by a constant current or maintained at a constant temperature. In either case, the heat lost to fluid convection is a function of the fluid velocity. By measuring the change in wire temperature under constant current or the current required to maintain a constant wire temperature, the heat lost can be obtained. The heat lost can then be converted into a fluid velocity in accordance with convective theory.

A MEMS Anemometer is a device comprising of an array of few thermal sensors with a central micro-heater, which enables us to estimate wind velocity, magnitude and direction when the fluid under purview is allowed to flow over it. A bulk machined dual axis hot wire anemometer consisting of our thermo-resistive elements arranged in a differential bridge configuration is presented. Where heating elements are often used on such devices, the sensor discussed here uses self-heating of the thermo-resistive sensing elements to provide the thermal energy required to generate the thermal plume and temperature differential across the surface of the device. The central heating elements used on typical integrated anemometers use valuable real estate on the die and adds complexity and potential failure mechanisms to the design. Removal of the central heating element reduces the number of elements that must be interfaced and frees up silicon real estate for other purposes, such as other sensing arrays. The thermo-resistive elements reported here are arranged to serve dual purposes as both the thermal sensing elements and the heating elements used to create the elevated surface temperature. The arrangement of the elements allows for dedicated heating elements to be omitted from the device without com-promising operation or sacrificing accuracy. Power consumption is also reduced along with an improvement in time response compared to some, more conventional, designs.

II. LITERATURE REVIEW

The thermal flow sensors used currently are mainly of three types, all of which comprise of heater and temperature sensors. They act as transducers interacting with the surroundings, leading to a change in temperature distribution due to heat carried away by the fluid. With increasing research in the field of silicon micro-machining the number of features that can be added to the devices have increased drastically, causing an increase in the functionality of the sensor, improving the response time. The response time plays a major role in acoustics and in turbulent flow. There are three basic types of thermal flow sensors:

- Anemometers
- Calorific flow sensors
- Time of flight sensors

Anemometers mostly consist of a single element which is heated and then its temperature variation is measured. There are two basic techniques to measure the wind velocity: Constant Temperature and Constant Power. The voltage varies proportionally to the boundary layer depending on the dimensions of the channel of the flow. Anemometer basic design is based on hot wire. The important characteristics are response time, sensitivity to magnitude and direction of flow. The hot wire in MEMS devices are replaced by a thin film deposited on an insulator to decrease the diffusion heat loss to the substrate mostly silicon nitride. There are three different approaches to solve this problem: 1. Cantilever type 2. Membrane type 3. Micro-bridges.

Two wire anemometers were further developed to reduce common disturbances by getting two different signals. This type of sensor consists of two hot wire anemometers to measure temperature difference between two points in the flowing fluid. Another reason to select two wire anemometers was to get a signal change when there is a change in flow velocity.

Calorific flow sensors are mass flow sensors transferring heat from the heater to the sensors creating a temperature differential. The relation of transported heat is dependent on the specific heat, hence, the fluid used is important. The calorific anemometer produces an output linearly dependent on the flow velocity for low Reynolds number flow i.e.; very low velocities. Calorific meters are designed so that distance between the sensors in very small ranging from 1nm to 10μm.

Time of flight sensors are calorific flow sensors operated in a dynamic mode. A heat pulse from the heater will deform the velocity profile and broaden it at the same time due to diffusion. The distortion of such a signal is only important at low velocities. In this type of sensor a heat pulse is fed to the heater thereby transferred to the fluid causing a delay at the sensor leading to the finding of true velocity.

III. DESIGN

The design and simulation of this micro-anemometer was carried out with certain aspects in mind.

As this research is in our initial stages it is necessary to prove the practicality of the principle at a small scale domain due to scaling effects. The idea was to simulate the novel design of the wind sensor. Certain assumptions were made: the primary one being that the micro-heater temperature sensor technology is assumed to be available to us on account of the extensive research work that has already been conducted in this field. Once we accept this assumption it is necessary to assume that for a valid packaging and fluid micro-channel system we can have an arrangement of thermal sensors and micro-heaters insulated from each other that produces a difference in temperatures in the micro thermal sensors in the arrangement such that is possible to identify wind velocity after retrieving data from a pre-identified data set. This power that was required to create a certain obtainable temperature difference on the micro thermal sensors were identified. This scenario is simplified into wind flowing in two components and each component of velocity is mapped from corresponding data plots. The power identified was then compared with results obtained from a theoretical calculation using governing equations of heat transfer and validating them. The simulation was performed in COMSOL multi-physics and the physics used were Conjugate Heat Transfer and Laminar flow. Inlet and Outlet conditions were specified for various flow vectors. Materials were assigned to insulation as silicon nitride and the thermal sensors and heaters were assigned with polycrystalline MEMS materials. Parametric sweep was conducted to plot the various temperatures at the heater and sensors to obtain a simulated data set.

IV. PARAMETERS USED

The three heat transport mechanisms that govern heat transfer in and out of material are conduction, convection and radiation. Out of these, convection is the essential mode of heat transfer to enable operation of this device hence its effect should be significant when compared to other modes of heat transfer. This is because only convection depends on the velocity of the medium. Both conduction and convection would only reduce the sensitivity and efficiency by introducing unnecessary heat losses.

Heat loss through radiation can be minimised by maintaining the component temperatures less than temperatures at which their effects become predominant (T<500 C) and the thermal effects can be reduced by having proper insulating material between the heating components and the substrate. Other efficient ways of providing insulation was using bulk reverse etching which significantly increases the conduction resistance.

So for getting an approximate value of temperature difference between the heater and the convective medium so as to verify the simulation results we validate the result obtained using theoretical correlations.

For this we assume a lumped heat capacity model for the heater. Since our analysis is based only on convective model we will neglect conduction and radiation effects.

From the simulation results obtained, we see that the heater surface has reached around temperature of 550K for a wind speed of 0.15 m/s. Now for these conditions we try to find out the rate of heat transfer from the central heater and see if this is equal to the power input to the heater.

V. USE OF COMSOL MULTIPHYSICS

The first model was developed to prove the possibility of the transfer of heat from the heater to the thermal sensors through the moving fluid. A simple array of silicon square chips insulated from each other through a highly non-conductive material was used. This was done to make sure that heat transferred to the micro thermal sensor was transmitted through the fluid and not through conduction.

A. Simulation 1

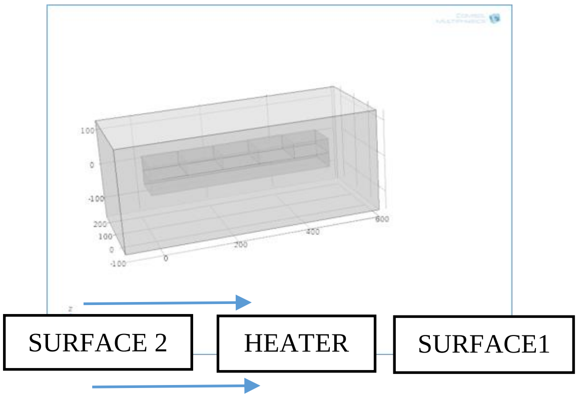
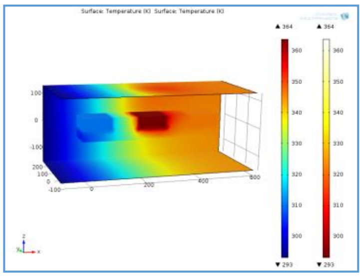
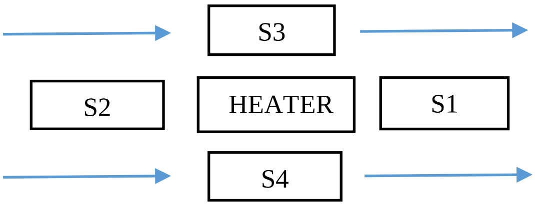


Figure 5.1

- Conjugate Heat Transfer Physics was used.
- An air velocity was simulated of 5cm/s
- Heating power of 0.0005W was provided to the central heater as a Heat Source.

- Boundary condition of air was introduced into the inlet at 20degrees Celsius temperature
- Thus it was proven that the surface 1 had a larger temperature than Surface 2





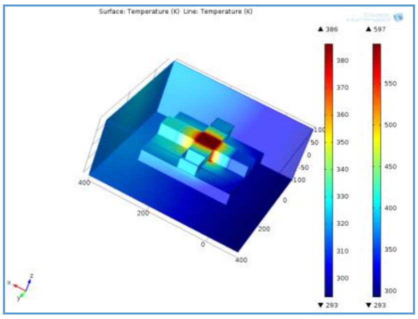
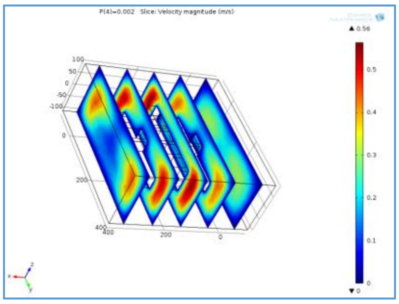


Figure 5.2

The above 3D temperature plot shows a difference in temperature of surface 1 and surface 2 while the temperatures of surface 3 and 4 are almost the same.Through a data analysis it is possible to derive the wind velocity and its component in x and y directions based on the temperature at each surface and at the heater as well.

C. Velocity Simulation



D. Plotting Temperature at Surfaces of Simulation 2

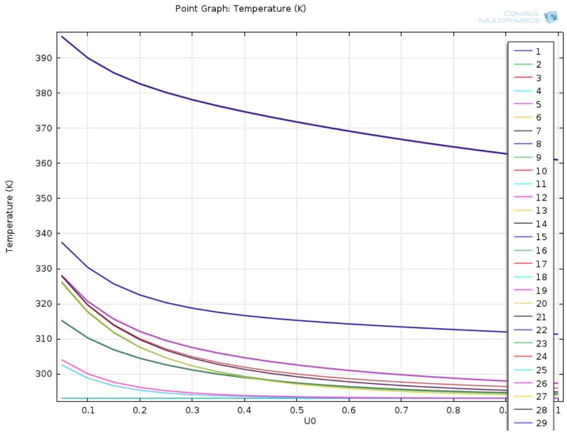


Figure 5.3

The above plot in fig shows variation of temperature at surfaces with inlet velocity.

VI. CALCULATION

The properties of air flowing over are measured at film temperature (400K)

L is the dimension of the heater, L = $60\text{x}10^{-6}$ m

Pr is called the Prandtl Number = 0.7

L is a characteristic dimension of the surface,

κ is the thermal conductivity of the fluid,

ν is the kinematic viscosity of the fluid,

μ is the dynamic viscosity of the fluid,

g is the acceleration due to gravity at the place of experiment,

ΔT = Temperature of heated surface – Temperature of environment, approximately = 250K

Heat convection can happen in two ways – forced and natural. Natural convection is independent of the free stream velocity. To see the influence of natural convection in our problem we calculate Gr (Grashoff's number). If Gr/Re2 << 1, then the effect of natural convection is negligible.

$Gr = g\ \beta\ \Delta TL^3 / v^{\ 2}$

$Gr = 9.8 \text{ x } 250 \text{ x } (60 \text{ x } 10^{-6})^3 / (400 \text{ x } (2.6\text{x}10^{-5})^{2)}$

Hence, $Gr = 1.95\text{x}10^{-6}$

$Re = \rho\text{x}V\text{x}D/\ \mu$

$Re = 0.9\text{x}0.15\text{x}60\text{x}10^{-6}/(2.3\text{x}10^{-5})$

Hence, Re = 0.35

$Gr/Re^2 << 1$ ➔ Natural convection effects can be neglected.

Therefore, heat transfer coefficient is given by Nuxk/L

$Nu = 0.664\text{x}Re^{0.5}\text{x}Pr^{0.33}$

For air at 400K, Pr = 0.7

Therefore, Nu = 0.35

Heat Transfer coefficient, h = 174.6 $Wm^{-2}K$

Rate of heat transfer = $174.6\text{x}(60\text{x}10^{-6})^2\text{x}250$

= 0.00015 W

This is of the same order as the value obtained in our simulation, which is 0.0005 W

Since the rate of heat transfer is proportional to the temperature difference between heater and the surroundings, the temperature vs heat input plot would be linear.

VII. CONCLUSION

A novel and simple model of a MEMS Anemometer has been obtained and a holistic simulation and analysis of the same has been done, thereby validating the results acquired in theoretical and experimental methods.

Firstly, the simulation was performed in a one dimensional array Anemometer followed by a detailed analysis of a two dimensional model. The relation between the temperature of the heating element and the power input with different inlet velocities was plotted and graph obtained was a straight line which was in accordance with what was predicted using the theoretical relations.

The direction of airflow can be inferred from measuring the temperature difference across sensors on opposite sides of the heater in both X and Y directions, using salient mathematical relations.

VIII. REFERENCES

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