Development of a Flow Sensor for Monitoring Human Respiration

Scott A. Kofoed
University of Utah Department of Bioengineering
University of Utah Department of Anesthesiology
Salt Lake City, Utah

ABSTRACT

Various technologies have been used to measure airway flow for human respiration. This paper presents a flow sensor (pneumotach) that is capable of continuous, bi-directional airway flow measurement proximal to the patient and used in a critical care environment. This paper presents some of the findings of the research that was done in the development of a new flow sensor for long term flow monitoring in the critical care environment.

INTRODUCTION

Various technologies have been used to measure airway flow for human respiration. Many of these techniques were developed strictly for precise short-term laboratory measurements. These applications require meticulous attention to detail including calibration and operator attendance at all time.

For the relatively dry gas, laboratory quality airflow measurements, great attention is placed upon accuracy, calibration, repeatability, and precision. Flowmeters that perform suitably in these environments include Fleisch and Lilly style pneumotachometers, hot wire anemometers, rotating vane spirometers, and ultrasonic vortex shedding flowmeter. Overall, in respiratory research the most widely used flow measurement device used is the Fleisch type differential pressure with a heated screen orifice.

A continuous, bi-directional airway flow measurement device that can be placed proximal to the patient and used in critical care environments has been of great interest. The continuous monitoring environment demands simplicity, reliability, ease of use and ability to continue working in wet, often mucous and sputum filled breathing circuits for long periods of time without operator intervention. These devices should be relatively inexpensive, have minimal dead space, work over wide flow ranges and require minimal or no calibration. Devices typically designed for the pulmonary function environment will generally not work well in continuous monitoring applications.

We have developed a new flow sensor for long term flow monitoring in the critical care environment. This paper presents some of the findings of the research that was done in the development of this new flow sensor.

METHODS

We began our research by defining the requirements and design constraints for a clinically acceptable flow sensor. These included:

We evaluated the current state of the art flow measurement technologies available for industrial and medical use. We decided that the paradigm of a differential-pressure, fixed-orifice flow meter was best suited our application. Since the fixed-orifice pneumotach does not require any moving parts, we thought that it was the best technology to adapt for clinical use for the following reasons:

Robustness - The sensor could be made in one solid piece. This would make the sensor easy to clean and to manufacture. We hypothesized that sputum on the sensing elements of other technologies could result in large measurement errors.

Calibration - We hypothesized that a flow sensor could be mass-produced using plastic injection molding techniques with sufficient tolerance so that minimal calibration, if any, would be required.

Cost - A plastic injection molded flow sensor can be produced inexpensively.

The disadvantages of the traditional fixed-orifice flow meter are a non-linear flow response, limited flow range and sputum changes orifices size and can occlude the pressure taps, and it is sensitive to the incident velocity profile. We focused our research on methods to overcome these limitations.

The non-linear flow response was overcome in the electronics and signal processing of the differential pressure signal. Since, the fixed-orifice flow sensor is repeatable from part-to-part, a detailed correction coefficient curve could be developed for a given sensor type. The flow sensor was characterized over the intended flow range. An array of correction coefficients was developed for each sensor type. The Reynolds Number of the flowing gas was used to index the array. Individual sensor characterization is not required if manufacturing tolerances are maintained.

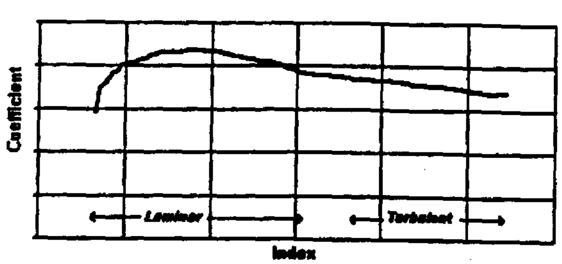

Figure 1 - Correction Coefficient Curve

The flow range of fixed-orifice flow meters can be limited due to the fact that the differential pressure varies as the square of the flow. High-resolution electronics were developed to measure 1 part in 500,000 of 10 inches H2O differential pressure. The special circuitry enabled flow resolution of <1% of reading over a 20:1 flow range. The electronics were optimized to minimize the effects of temperature drift and electromagnetic immunity.

The traditional fixed-orifice flow meter consists of an orifice plate and pressure taps inside of a flow tube or pipe. The orifice plate looks like a washer being a flat, circular plate with a hole in the center. Shown below is an example of two different orifice plates.

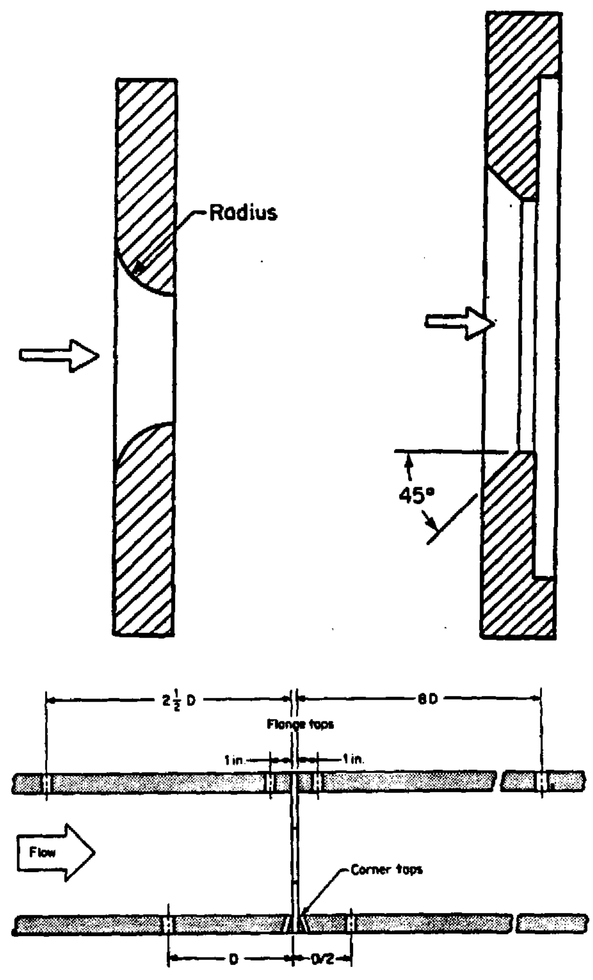

Figure 2 - Fixed orifice plates used in industrial use. Pressure taps shown.

The differential pressure can be tapped from various locations across the orifice plate. The picture below shows pressure variations associated with a fixed-orifice plate. Notice that the downstream pressure tap measures a large negative pressure relative to the overall pressure loss.

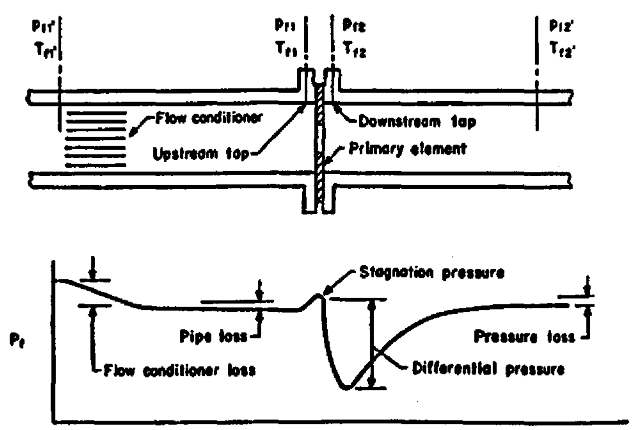

Figure 3 - Pressure variation about orifice plate.

Pressure taps are placed on the wall of the pipe to measure static pressure. To provide a true static pressure measurement the hole for the pressure tap must be correctly formed. Taps should be orthogonal to the pipe wall. The hole must be round and free of burrs or wire edged.

Raised Pressure Taps

Traditional orifice plate design can not work in a clinical setting due to moisture and sputum fouling the pressure taps. We built and tested a fixed orifice design with raised pressure taps. We placed pressure taps by using a .062" thin wall aluminum tube through the wall of a 15mm flow tube. Pressure taps were placed .25" upstream and downstream of a 0.40" orifice plate. The top of the pressure taps were raised from the wall of the flow tube and tested at a height of 0.125" and 0.250". Differential measurements for various flow rates were compared for the different pressure tap heights to the flush tap.

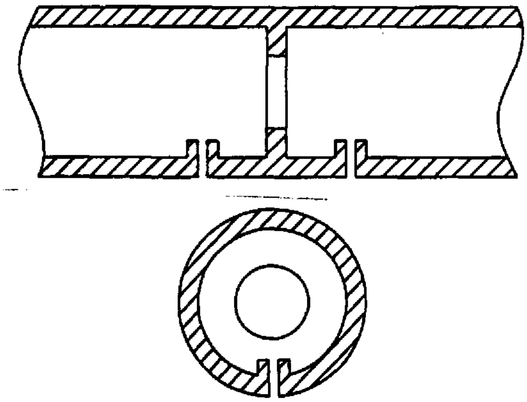

Figure 4 - Flow tube with raised pressure taps.

Pressure Taps on a Raised Plane

Static pressure taps are placed on the wall of a flow tube because the velocity on the wall surface goes to zero due to well-known viscosity and shear stresses on the fluid being measured. We hypothesized that the static pressure taps could be placed on a raised plane in the gas flow. To form a raised plane we placed a narrow ridge along the interior of the flow tube. Pressure taps were formed in this raised plane. A 15mm flow tube with a 0.40" orifice plate with pressure taps on a raised plane was compared to a flow tube with standard pressure taps.

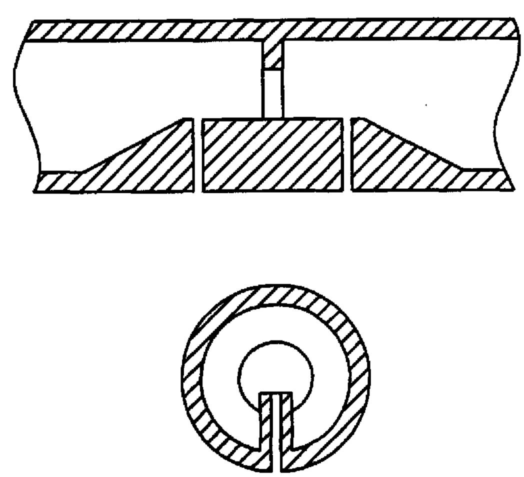

Figure 5 - Pressure taps on raised plane.

Inverted Orifice: Obstruction on Center Axis of Flow Tube

Traditional orifice plates create an obstruction to airflow on the wall of the flow tube with an opening on the center axis of the flow tube. To allow sputum and moisture to move freely along the wall of the flow tube we desired to move the obstruction to the center axis of the flow tube leaving the walls smooth. Using the pressure taps on the raised plane we tested a circular flow obstruction attached to the raised plane.

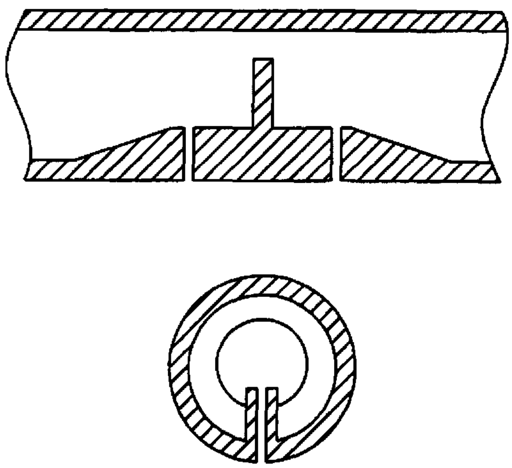

Figure 6 - Circular obstruction on raised plane with pressure taps.

Flow visualization studies were performed on a 10x mock up of the circular obstruction using a surface smoke injection technique. Flow structures and patterns were visualized by creating sheets of light using a laser and a Pyrex rod.

Symmetrical Raised Plane with Rectangular Obstruction

We combined the findings of the previous studies and developed a geometry for a flow sensor. A raised plane was used for the pressure taps and mirrored across the center axis was a second raised plane. The second raised plane was provided for symmetry. A rectangular flow obstruction was placed between the pressure taps extending to and slightly beyond each of the raised planes.

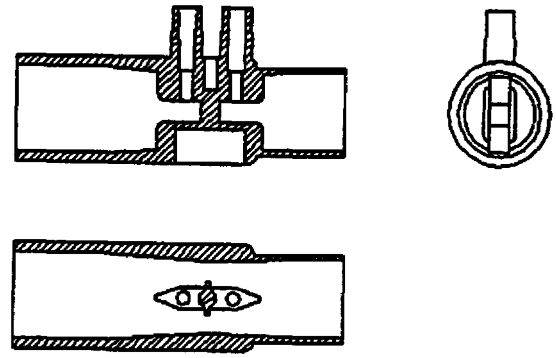

Figure 7 - Symmetrical raised planes with rectangular flow obstruction.

RESULTS

Raised Pressure Taps

The raised pressure taps using the thin walled aluminum tubing did not compare well to the standard pressure tap. The raised pressure taps were very sensitive to the height from the wall. The measured differential pressure decreased with increasing tap height. Pressure readings were erratic. Some changes in the inlet velocity profile resulted in an inverted differential pressure signal.

Pressure Taps on a Raised Plane

The pressure taps on the raised plane with the orifice ring on the wall of the flow tube resulted in decreased measured signal for a given flow rate when compared to the standard pressure tap. As the raised plane height was increased towards the center axis of the flow tube the measured differential pressure signal decreased although the signal was stable and repeatable.

Inverted Orifice: Obstruction on Center Axis of Flow Tube

The flow obstruction placed on the raised plane provided excellent signal strength for all configurations tested. Differential pressure measurements were stable and repeatable. However, the circular flow obstruction resulted in unstable differential pressure readings when the gas velocity was in the transitional flow range (Re = 2000 to 4000).

Flow visualization studies of the circular obstruction revealed that vortices form downstream of the flow obstruction. In the plane perpendicular to the surface of the raised plane for the pressure taps, a single vortex formed with a height of the obstruction diameter. On the center axis, in the plane parallel to the surface of the raised plane for the pressure taps, dual vorticies formed with a height of 1/2 the obstruction diameter. During transitional flows (Re = 2000 to 4000) these vorticical structures appeared unstable.

Symmetrical Raised Plane with Rectangular Obstruction

The flow sensor with symmetrical raised plane with a rectangular obstruction provided a stable differential pressure measurement even through transitional flow velocities. The flow characterization coefficient curve was smooth and continuous.

CONCLUSION

Pressure taps that are not orthogonal to a surface where the gas velocity goes to zero near the surface provide poor pressure measurements. Pressures are lower than expected. Perhaps this is due to Bernoulli effects where the pressure decreases due to the raised velocity as the gas goes up and over the raised tap.

With the raised plane forming a surface that extends from one pressure tap to the other pressure tap, the measured differential pressure went to zero. Along the surface of the raised plane the velocity of the gas goes to zero due to viscosity, friction and shear stresses. The raised plane for the pressure taps worked best when the flow obstruction was connected to the raised plane disrupting the smooth plane between the two pressure taps.

The circular flow obstruction worked well except for transitional flows (Re = 2000 to 4000). From the flow visualization studies we concluded that this was due to the unstable flow structures formed downstream of the flow obstruction. We also concluded that allowing the flow structures to only form in a restricted two-dimensional pattern would result in a more continuous and stable fashion throughout the flow range.

The flow sensor with symmetrical raised plane with a rectangular obstruction provided a stable differential pressure measurement even through transitional flow velocities. The flow characterization coefficient curve was smooth and continuous. This flow sensor design provided the best overall results of all the configurations tested.