AUTOMATION OF A WATER FLUME USING MICROCOMPUTER BASED DATA ACQUISITION FOR SNOW AND WIND ENGINEERING

Michael J. Soligo, B.A.Sc., M.A.Sc., P.Eng.
Franklyn H. Theakston, B.A.Sc., M.A.Sc., P.Eng.
Ewart Brundrett, Ph.D., P.Eng.[1]
Paul Kankainen, B.A.Sc., M.A.Sc.[2]

FRANK H. THEAKSTON & ASSOCIATES INC.
CONSULTING ENGINEERS
335 LAIRD ROAD
GUELPH, ONTARIO
N1H 6J3

ABSTRACT

This paper describes the automation of the water flume of Frank H. Theakston & Associates Inc. for snow and wind engineering studies. The measurement of building pressures and pedestrian level velocities are shown to be direct extensions of existing wind tunnel technology through the correct application of fluid mechanics principles. It is shown that water flumes can be configured to measure local building and velocity pressures by means of an appropriate pressure transducer, scanivalves, purging software and hardware, and a reference flume wall static pressure. It is noted that Reynolds modelling can be conducted at 1/15th of the velocity required in a wind tunnel due to the favorable ratio of water-to-air kinematic viscosity. Further, it is noted that water flumes require less power, and less space than wind tunnels for a given size of model test section, and that minor blockage effects are self correcting via the free surface of the water. Finally, through automation of data acquisition it is possible to equip a water flume test facility that can obtain, fully reduce, and report all measurements of snow accumulation, building wind pressures, and pedestrian level velocities.

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[1] Professor, Department of Mechanical Engineering, University of Waterloo.

[2] Research Engineer, Department of Mechanical Engineering, University of Waterloo.

1.0 INTRODUCTION

Open channel water flumes have become a very important part of environment engineering. For approximately the past 100 years environmental and hydrological engineers and scientists have developed several applications for this apparatus. Several government operated companies as well as private consultants use the water flume to study a vast array of hydrological concerns. These include Froude scale modelling, pollutant dispersion in various water ways, friction factors and resistance as they pertain to flow depths and discharge, sediment transportation, fish ladders, hydro power generation, erosion studies, energy dissipation, and many more applications.

Approximately 23 years ago Professor Frank Theakston[1] developed a new application for the open channel water flume. Professor Theakston applied the basic laws of fluid mechanics modelling to use water flow in an open flume to study wind driven snow. The water flow modelled the wind motions around the structures and fine grained silica sand modelled the snow particles and drift patterns. Both qualitative and quantitative results were obtained of snow patterns and drift accumulations using the modelling techniques and the investment of many years of painstaking observation and documentation. The National Research Council recognized the significance of Theakston's pioneering work and supported ongoing research to continue the development of the water flume as a modelling facility for snow and wind engineering.

During the past 23 years an author of this paper (Theakston) has been involved in thousands of snow accumulation studies using models, silica sand, and an open channel water flume known as a "snow and wind simulator". The success of wind and snow accumulation simulation in an open water channel stimulated further applications to wind engineering. The authors perceived that a water flume could be used to conduct wind related studies such as building pressures for various approach wind profiles. These studies have been conducted in wind tunnels for years and it was recognized that the wind tunnel techniques could be applied to measurements in water flow, provided that appropriate pressure transducers and technology could be established for water.

Extensive research of pressure measurement in water flow has been conducted by the authors permitting the following wind engineering applications to be accurately and reliably obtained:

1. The determination of wind forces and pressure coefficients on building surfaces.
2. The determination of velocities on and around a given building complex.

This paper discusses the application of an open channel water flume to wind engineering studies. Included is a discussion of the simulation and data acquisition system developed by the authors as well as a brief review of conditions that must be satisfied for successful modelling in a water flume.

2.0 MODELLING OF ATMOSPHERIC WINDS

2.1 Power Law

To conduct any form of wind engineering study by way of model simulation it is imperative that the appropriate boundary layer conditions be modelled in the water flume or wind tunnel. In 1885, Archibald[1] reported that a power law could be used to correlate wind speeds that he observed from anemometers hung from kites. This correlation is given by equation 1:

$$\left(\frac{\overline{U}}{\overline{U_g}}\right) = \left(\frac{Z}{Z_g}\right)^{\frac{1}{n}} \qquad (1)$$

Where:

$\overline{U} =$ local mean horizontal velocity at elevation Z,

$\overline{U_g} =$ reference mean velocity at elevation Z_g,

$Z_g =$ the distance above the surface at which the reference velocity is taken,

$n =$ the power law exponent defined by ground roughness,

$\alpha = \frac{1}{n}$ the often quoted inverse power law exponent.

Since that time several researchers have determined that a range of power law exponents are applicable when representing surface roughness conditions observed from very smooth ($n = 10$) to very rough due to high rise buildings ($n = 2$). Empirical data and experience are essential for a correct evaluation of the power law exponent, which often depends on the wind direction at a location possessing direction dependent roughness.

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[1] Then at the University of Guelph, at Guelph, Ontario, Canada.

Toronto Ontario is a good example, since a smooth flow exists from the south off of Lake Ontario, whereas rough flow conditions apply for the remaining wind directions.

Cermac[2] recommended the data correlation of Davenport[3], which was based on a characteristic surface roughness height Z_0. The research of Rae and Pope[4] gave very similar results to those of Davenport[3]. Table 1 lists data determined by these workers along with the expected height of the boundary layer Z_g. The power law provides a convenient method for boundary layer classification; however, it does have certain limitations:

1. The power law does not represent velocities well for values of Z/Z_g near zero or unity. Near the surface the boundary layer gradient is incorrectly modelled, i.e., the wall shear stress prediction is incorrect, while at the edge of the boundary layer the curve fit is not asymptotic to $\overline{U_g}$.
2. The power law exponent "n" can vary vertically through a typical urban boundary layer.
3. The power law does not make allowance for Coriolis acceleration of the flow. This can lead to a 5° twist of the boundary layer over an elevation change of 200 m (Rae and Pope[4]).
4. The power law does not make allowance for heating and cooling of the boundary layer by atmospheric factors, which must be included for inversion studies, etc., and which can only be ignored for strong wind conditions (Rae and Pope[4]).

Investigator	Surface Type	n	$1/n = \alpha$	z_g
Davenport	Open Sea	10.0	0.10	—
[3]	Flat Country	6.25	0.16	275 m
”	Forest	3.57	0.28	395 m
”	Urban	2.50	0.40	515 m
Rae and	Open Country	6.67	0.15	85 m
Pope[4]	Low Buildings	3.57	0.28	365 m
”	Urban	2.50	0.40	517 m
Laminar	Flat Plate	2.00	0.50	—
Turbulent	Plate Low Re	7.00	0.14	—
[5]	Plate High Re	10.0	0.10	—

Table 1: Reported boundary layer heights and power law coefficients

Regardless of these limitations Cermac[2] believes that the power law provides adequate criteria to study wind loading on buildings in water flumes and wind tunnels, for strong wind conditions. Rae and Pope[4] conclude that the power law is adequate as well, provided that the boundary layer accurately describes the chosen power law exponent to a height of 1.5 times the tallest building of the model setup and that thermal gradient effects can be ignored.

2.2 Boundary Layer Criteria for Model Analysis

From a theoretical perspective there are several conditions that should be met when modelling atmospheric boundary layers. These conditions require the real and model flows to be subject to the following:

1. Undistorted scaling of geometry,
2. Equal ratios of viscous and inertial forces or Reynolds number,
3. Equal Coriolis force effects as described by the Rossby number.
4. Equal thermal effects as described by the Richardson number,
5. Equal Prandtl numbers,
6. Equal heat transfer ratios or Eckert numbers.

In practice, however, wind engineers normally study strong wind conditions in a water flume or wind tunnel and need only be concerned with geometric scaling and the Reynolds number (Rae and Pope[4]). However, it must be noted that cyclonic flows such as tornadoes and hurricanes cannot be modelled in a narrow channel water flume or wind tunnel, if indeed in any laboratory environment.

2.3 Establishing Approach Boundary Layers

The development of boundary layers in water flumes and wind tunnels have been carried out for years. Boundary layers are characterized by flow parallel to a plate or other surfaces that do not exhibit three dimensional geometric effects or support pressure gradients in the direction of flow.

One of the first methods of establishing boundary layers examined the flow of water and wind over a smooth flat plate. However, the development length required to obtain realistic depths of boundary layers for model studies was too great for water flumes and wind tunnels when achieved by a smooth plate.

Cermac[2] examined the effect of placing cubes on the approach surface of his wind tunnel to thicken the boundary layer and to obtain smaller values of the power law exponent "n". The tunnel that he described had a very long approach length of 25 m and was operated at a free stream velocity of 10 m/s, so that the boundary layer Reynolds number was $Re = 1.67 \times 10^8$.

He observed that the boundary layer thickness at the end of the approach length, δ, could be correlated by a logarithmic function of roughness height in metres as;

$$\delta = 0.8 + 0.227 \log(h) \qquad (2)$$

where h is the roughness height in metres.

Cermac[2] also concluded that roughening the approach length provided an excellent simulation of the turbulent structure of atmospheric boundary layers in strong wind conditions.

To shorten the approach length several investigators have examined devices such as strakes that are placed at the start of the rough surface. The strakes rapidly thicken the boundary layer when followed by surface roughness cubes or blocks.

Standen, Dalgliesh and Templin[6] presented an early version of an acceleration system for boundary layer growth in 1971. It consisted of a boundary layer fence and triangular rear leaning vortex generators at the start of the surface. These were followed by roughness cubes. Standen *et al.*[6] obtained acceptable modelling of the mean and turbulence properties of atmospheric boundary layers for considerably reduced approach lengths. However Cermac[2] cautioned that very short approach lengths may provide good mean flow simulation without adequately developing the turbulence structure. He went on to note that strakes alone cannot provide a boundary layer that can be sustained. Evidently the surface roughness cubes sustain the thickened boundary layer after it is formed by the strakes.

A later work by Standen[7] simplified the design and installation of high drag strakes placed at the start of the approach length and codified the positioning and size of the roughness blocks in proportion to the strake size and spacing. This treatment has become a standard adopted by many researchers including Cermac[2], Rae and Pope[4], and the present authors (Photographs 1,2, and 3).

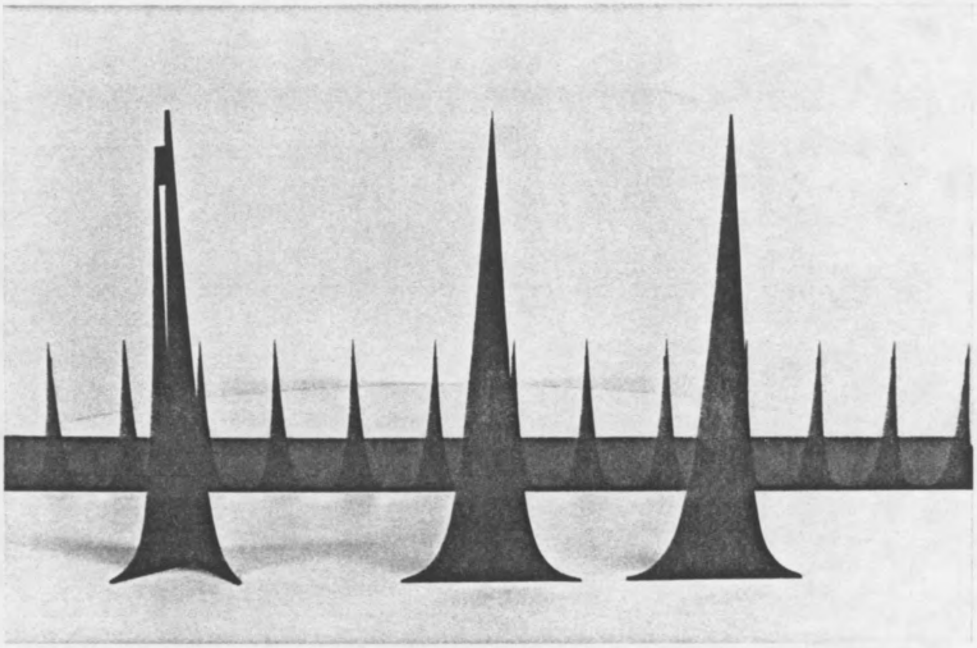
2.4 Comparison of Open Channel Flumes to Wind Tunnels

Until Theakston[8] developed the method of simulating snow and wind in an open channel water flume for the purpose of determining snow accumulation on scaled models, the wind tunnel was the primary instrument used for snow simulation studies. Today the wind tunnel is the major apparatus employed for wind engineering studies other than snow accumulation simulation. However, there are several characteristics of the open channel water flume which prove that this device is superior to the wind tunnel for certain aspects of wind engineering and equivalent for the remaining applications.

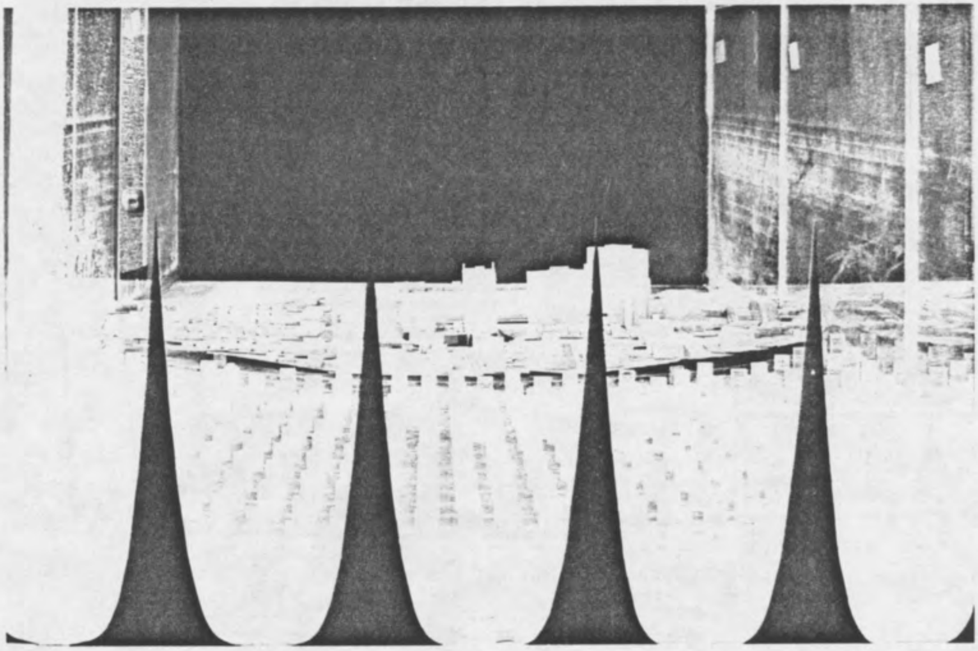
Qualitative studies are better suited for the water flume as the visualization of wind characteristics and the flow of eddy currents are easily identified. The injection of coloured dye into the water highlights the simulated wind flow. With a wind tunnel the injection of coloured tracer gases is more difficult to achieve at concentration levels that permit effective photography. Also the flow of water in a flume can be much slower for a given Reynolds number thereby permitting easier visualization of the streamline and eddy patterns. This can be seen from the fact that the kinematic viscosity of water at room temperature is $\nu = 1.0 \times 10^{-6}$, whereas the kinematic viscosity of air at room temperature is $\nu = 1.5 \times 10^{-5}$. Hence, for a given model size the air velocity must be 15 times greater than the water velocity in a flume to obtain a specified Reynolds number.

This observation leads to several benefits for flume operators;

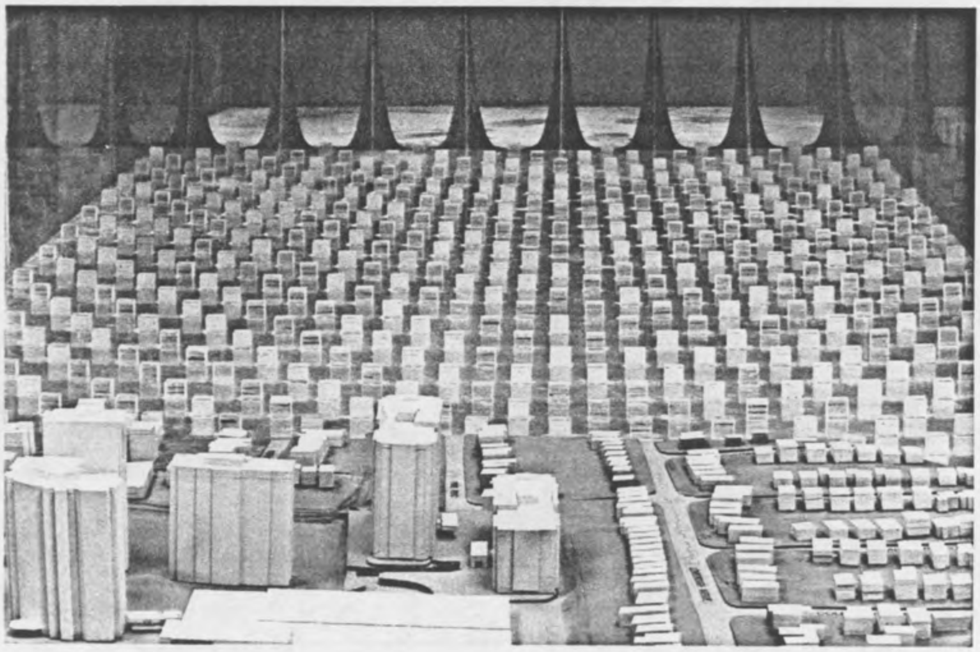
1. The operating costs of a flume are generally lower than for a wind tunnel for a given model Reynolds number.
2. Low velocity data can be reliably obtained in a water flume by dye tracing techniques.
3. The free surface of a water flume adjusts for small blockage effects of models place in the flow and clearly indicates if the model blockage is excessive. Wind tunnels require automated compliant walls or a very large test section to model area ratio to achieve a similar level of blockage control.
4. Hence, the total space occupied by a water flume is significantly less than that of either a closed



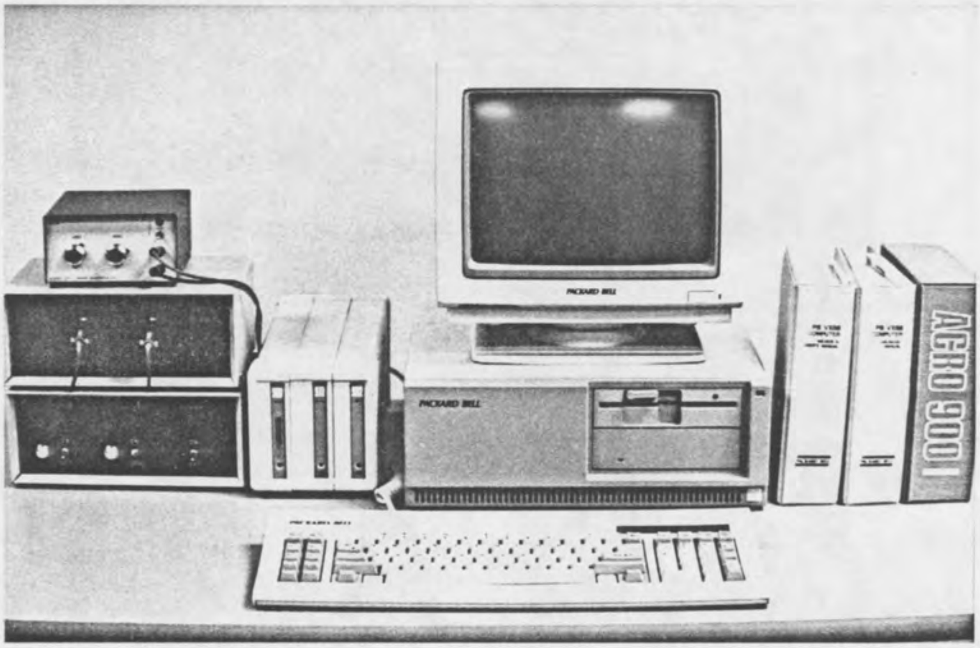
Photograph 1. Boundary layer development strakes after Standen[7] showing 300 mm strakes foreground (side view at left) and an array of 150 mm strakes in the background.



Photograph 2. View downstream from an array of 300 mm strakes to a model installed in the water flume of Frank H. Theakston & Associates Inc..



Photograph 3. View upstream from a model toward roughness blocks and 300 mm strakes in the water flume of Frank H. Theakston & Associates Inc..



Photograph 4. The automation equipment used by Frank H. Theakston & Associates Inc.. On the left power supplies and switching relays for the scanivalves (not shown). Next the data logger and then an 8088 8 MHz MS-DOS microcomputer used to control and record the experiment.

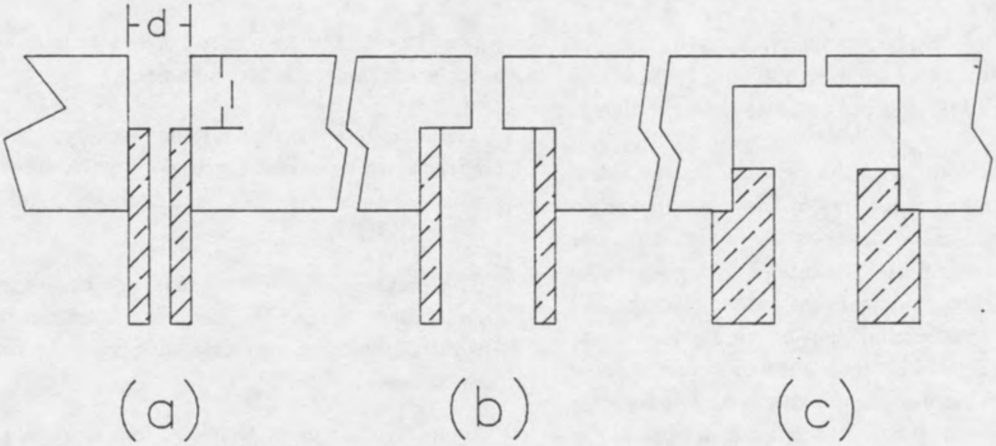


Figure 1. The wall static pressure tap geometries of: (a) Allen and Hooper[13], (b) Shaw[16], and (c) Livesey[17].

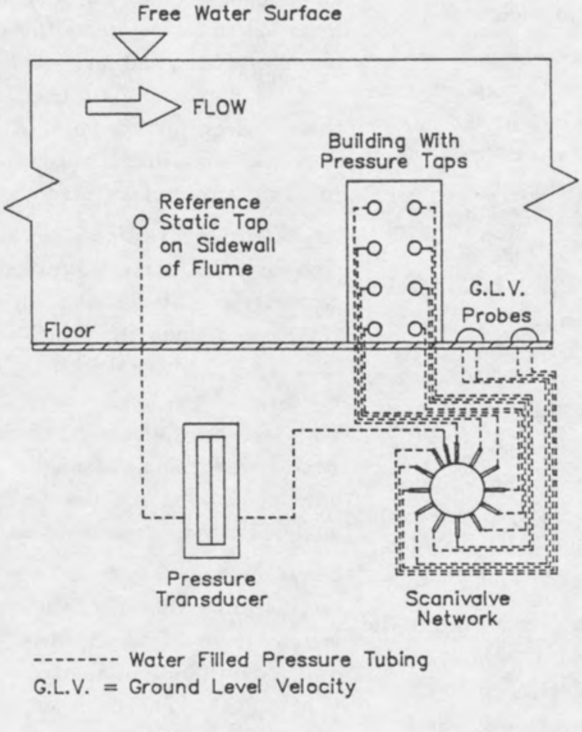


Figure 2. Experimental setup to obtain pressure measurements from a water flume. The pressure signal is processed by a data logger and microcomputer.

or open return wind tunnel for a specified model size.

5. A water flume is not influenced by the opening of doors or other room pressure disturbances.
6. The excellent thermal capacity and heat transfer properties of water ensure that temperature rise due to frictional dissipation is never a problem.

Theakston[9] has compared the results of snow simulation in a water flume to that of snow simulation in a wind tunnel and from his work has stated that the water flume has a definite advantage with respect to experimental control, efficiency of model testing, and the accuracy of the results. The silica sand and water combination creates an excellent simulation of snow accumulation. Wind tunnel experts have tried everything from aluminum powder to crushed walnut shells to represent snow in wind tunnel experiments and still continue to search for good snow representative materials.

The aforementioned statements have identified some of the benefits of an open channel water flume for wind engineering studies. However, for the purpose of wind pressure and velocity measurements the wind tunnel has been the apparatus used by wind engineers.

However, the authors of this paper have developed a method of adapting the water flume to conduct pressure and velocity studies, as described in the following section. These capabilities of a water flume are in addition to the well documented investigation of snow accumulation as described by Theakston[8][9][10][11].

3.0 THE MEASUREMENT AND PREDICTION OF SURFACE PRESSURE AND VELOCITIES IN WATER FLUMES

3.1 Measurement of Static Pressures

An extensive literature survey was conducted recently by Chue[12], of all pressure measurement techniques for fluid flow. His review of wall static taps has served as the basis for this report and recommended wall tap geometry.

Allen and Hooper[13] examined a very simple wall static pressure tap, (tap), which consisted of a hole drilled through the wall of a pipe. A pressure tube of the same diameter was fitted part way into the hole from the rear, (Figure 1a).

The design is very rudimentary, with two controlling tap parameters;

1. the hole diameter **d**,
2. the hole depth to the tube **l**.

This geometry of tap has not received general acceptance for accurate measurements since;

1. The ratio l/d was shown to have a very significant effect upon systematic errors of pressure measurement. The errors grew with increasing values of $0.5 < l/d < 6.0$.
2. The position of the tube may not be accurately controlled, hence l/d can vary from tap to tap resulting in large variations of pressure measurement error.
3. Chue[12] concluded that this tap hole geometry led to the largest absolute errors of pressure measurement due to the formation of eddies in the tap cavity, i.e., the geometry created the strongest eddy structure of all reported taps.

Rayle[14] showed that static pressure measurement errors were a minimum for 0.4 mm diameter holes fashioned to the geometry of Allen and Hooper[13]. Smaller holes led to larger errors, possibly due to his method of construction, and larger holes led to increased errors up to a diameter of 1.0 mm. However above 1.0 mm there was no further observed increase in error. The work was somewhat confusing, except to note that very small taps are not an advantage.

An extensive investigation was conducted by Ray[15], who showed that static pressure error of taps of a given geometry can be described by a tap Reynolds number Re^+, based upon the orifice diameter of the pressure tap, the wall shear velocity $\sqrt{\tau_0/\rho}$, and the kinematic viscosity of the fluid. Ray's[15] work clearly showed that taps have errors which increase with wall shear stress and with hole diameter. In fact his tap Reynolds number Re^+ has become the basis for all modern error analyses of wall pressure measurements.

Shaw[16] made a systematic experimental examination of hole dimension effects upon pressure measurement errors. He used an improved tap based upon a short orifice depth and an enlargement to the pressure tube (Figure 1b). The enlargement effectively eliminated deep eddy formation in the tap, and ensured that the pressure tube could be accurately positioned. This ensured that the ratio l/d could be accurately specified by careful machining. The design of Shaw[16] has been the basis for most pressure tap installations during the past 25 years.

Livesey *et al.*[17] examined a refinement of Shaw's[16] work. They constructed taps with a large reservoir behind the orifice of the wall face (Figure 1c). The reservoir diameter was larger that the pressure tube inside diameter in each case. They reported that the enlarged reservoir created further improvements in the control of static pressure errors. For l/d ratios of 0.5 to 1.0, they report that the errors are quite small for $Re^+ \leq 100$, being typically 0.02 or less of the wall shear stress.

Shaw[16] made a further contribution to pressure tap technology by noting the effect of burrs, radii, hole slope and chamfers upon the measurement error as listed in table 2 for an l/d ratio of 2.

Static Tap Modification	Measurement Error %
0 radius of lip	0.0
1/4 d radius of lip	0.2
1 d radius of lip	1.1
30 deg slant upstream	0.3
45 deg slant upstream	0.4
30 deg slant downstream	0.0
45 deg slant downstream	-0.1
upstream burr	- error
downstream burr	+ error
1/8 d deep chamfer	-0.1
1/2 d deep chamfer	-0.3

Table 2: The influence of tap lip geometry on the measurement error of static pressure, from Shaw[16].

The chamfering tool used by Shaw[16] had a tip angle of 82°. The upsteam or downstream slant was produced by drilling the tap at the specified angle from the normal to the surface.

Any tap geometry that is used should be designed such that it can be manufactured with a minimum of time and effort, yet, which adequately retains the accuracy of the best features of Shaw[16] and of Livesey *et al.*[17].

Pressure taps that are constructed on building walls can be connected to a scanivalve via water filled tygon tubing as shown in Figure 2. The scanivalve should be set up to measure pressure differentials, using a flume wall static pressure as a reference for one side of the pressure transducer.

It is interesting to note that the elevation of the pressure transducer and all wall static pressure taps need not be specified to obtain a pressure differential. Figure 3 shows a pressure transducer connected to a building pressure tap at an elevation h_b below the free surface of the water flume. The other side of the pressure transducer is connected to a flume wall static tap at an elevation h_w below the free surface, and the pressure transducer is located at an elevation h_t below the free surface. Any difference in elevation between the building and wall static pressure taps is automatically cancelled by water filled tubing connecting the taps to the pressure transducer, (i.e. $h_w + h_1 = h_b + h_2 = h_t$). Hence, any difference in pressure between the building and flume wall static pressure taps is entirely due to the dynamic pressure of the local flow acting on the building.

Care must be exercised to ensure that the scanivalve only permits pressure differentials to be measured when port switching occurs, otherwise, the pressure transducer would have to be capable of withstanding the full static pressure of the water column above it to the free surface of the flume. However, then the accuracy of the transducer would probably be less than that required to measure flow induced building pressures and pedestrian level velocities. It is recommended that deaerated distilled water be used to purge all pressure lines to remove air bubbles and to clean the pressure tap orifices by outward venting of water. The purge process should be conducted after a model has stood in air for more than a few minutes and certainly before the first pressure measurement tests of the day.

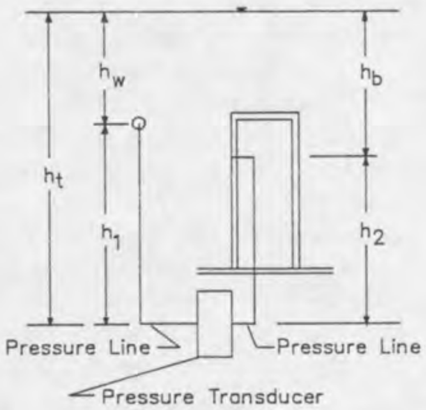


Figure 3. A schematic representation of typical locations of building and flume wall pressure taps and their connecting tubing with respect to a pressure transducer (multiple lines and a scanivalve are not shown).

3.2 Measurement of Velocity and Shear Stress

In 1732 Henri Pitot recognized that a tube bent to face the oncoming stream, measured the total or impact pressure of the flow at the open end of the tube, provided that there was a sufficient stem length to prevent flow interference at the tube opening. Since that time researchers such as Zahm[18], Prandtl and Tietjens[19], Bryer and Pankhurst[20], Chue[12], and Gracey[21] have experimented on shapes and designs of Pitot tubes and have provided extensive calibrations. Gracey[21] extended his investigation to examine the permissible flow yaw angle of probes while retaining an error of measurement of less than ±1%. He concluded that right angle faced probes with an internal chamfer of 15° and no external burrs were accurate to ±1% up to yaw angles of 27.5°.

Measurement of total pressure is described by the Bernoulli equation. For ideal flow and neglecting elevation changes the Bernoulli equation states that;

$$P_{static} + \frac{\rho\,\overline{U}^2}{2} = P_{total} = \text{Constant} \qquad (3)$$

Where;

P_{static} = local static pressure (see section 3.1),

P_{total} = total pressure,

ρ = fluid density,

$\overline{U}$ = mean fluid velocity at the probe opening.

Ideal flow is not common in practice, therefore, a correction factor (C) is necessary to relate the actual fluid velocity to that provided by the Bernoulli equation. A comprehensive survey conducted by Chue[12] provides a Reynolds number correction for Pitot tubes of various designs, and indicates that rounded front tubes required a correction factor for $Re < 100$, whereas blunt faced tubes only require correction for $Re < 20$. The Reynolds number is constructed from the fluid kinematic viscosity, approach flow velocity, and tube outside diameter as $Re = (\overline{U}\,D)/\nu$, and is valid for large ratios of tube inside to outside diameter (d/D).

A Reynolds number > 20 is easily achieved in a water flume. For example if a 2.1 mm outer diameter tube is selected then $\overline{U} > 1.9 cm/s$ satisfied this requirement. Velocities $< 1.9 cm/s$ will only occur for distances less than 0.029 mm from a wall for a free stream velocity of 20 cm/s and for a 1/4 power law boundary layer profile. It should be noted that a free stream velocity of 20 cm/s is realistic since it provides very good pressure and velocity signals in water flow. Also, the probe diameter of 2.1 mm effectively prevents any measurement closer than 1.05 mm from a wall. Hence, the region of viscous flow correction of Chue[12] is never required in pressure and velocity investigations in water flumes.

The measurement of the total pressure and static pressure permits the determination of velocity from the Bernoulli equation with correction factor (C) as;

$$\overline{U} = \sqrt{\frac{2\,C\,(P_{total} - P_{static}}{\rho_{water}}} \qquad (4)$$

An example water flume velocity profile downstream of obstructions is shown in Fig. 4. Note that the experimentally determined velocity profile downstream of the obstruction does not obey exactly a power law, even though it is best approximated by a value of n = 3.8. This evidence clearly indicates the need to obtain velocity profiles for wind and snow engineering studies that require definitive environmental specifications.

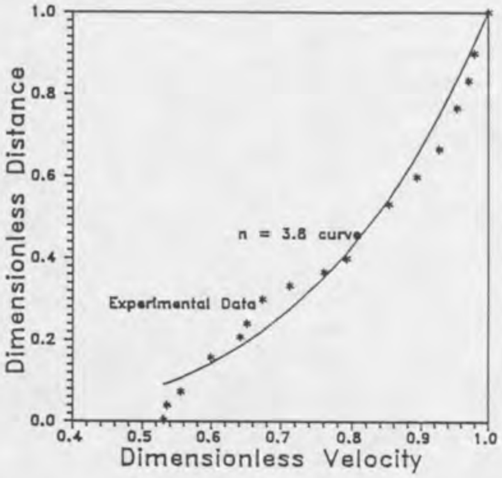


Figure 4. Velocity profile obtained downstream of a set of large roughness blocks in the water flume of Frank H. Theakston & Associates Inc. Also shown is the best fit power law velocity profile.

When required, surface shear stresses can be obtained by using Preston tubes and the correlations of Patel[22]. The Preston tube is placed on the desired wall to measure near wall total pressure and thus requires a nearby static pressure tap to obtain the near wall dynamic pressure. The probe geometry is quite simple, being a right angle faced tube of 1 to 3 mm diameter with an inside to outside diameter ratio of typically 0.6 to 0.9

(Patel[22]). The correlations of Patel[22] provide the wall shear stress directly from the velocity measured by the probe. Preston tubes have been used for more than 20 years and have received wide acceptance.

3.3 Pedestrian Level Wind Velocities

Davenport and Isyumov[23] discuss the theory and application of pedestrian level wind velocity studies and structural surface pressure studies to wind tunnels as do Isyumov and Davenport[24]. These findings have been adapted by the authors for water flume studies using fundamental fluid mechanics principles.

Pedestrian level wind velocity studies analyze winds near ground level and relate them to pedestrian comfort as defined by location, season, and activity. To conduct this type of study two major sources of data are required, the first being actual meteorological data of the area. These data are commonly collected by government agencies, such as Environment Canada, at specific collection stations. The data are collected on a continuous basis and are readily available.

The second type of necessary data are velocity factors obtained for various ground level locations. These factors are determined experimentally and applied through a sequence of mathematical formulations to the existing macroclimatic data. It is the determination of these factors that require model techniques and the use of a wind tunnel, or now, a water flume. Special pressure probes have been developed by the authors for ground level velocity measurements in water flumes. The probes are secured in the base of the model at the pedestrian level of 1.5 to 3.0 m full scale height and at predetermined locations. The probes are equipped with total and static pressure taps to obtain pedestrian level velocities via the Pitot tube equation (equation 4), and their calibration coefficient (C). A number of pedestrian level velocities can be obtained in one experimental run by using a scanivalve and appropriate control software. The pressure signal of each probe is read as a voltage from the pressure transducer by the data logger. The value of the voltage is then converted to a velocity reading by the microcomputer and stored for subsequent evaluation of results and report preparation.

All velocities measured near buildings or at the pedestrian level as well as building pressures are related to the velocity or velocity dynamic pressure of the approach boundary layer at a specified elevation. The velocity, often called the gradient velocity by Davenport[3], occurs at approximately 500 m above the ground for rough and built-up terrain, but should always be at an elevation of at least 1.5 times the tallest building in the model study (Rae and Pope[4]). In the case of building pressures the dynamic pressure of the reference or gradient velocity is used to create a dimensionless pressure coefficient as described in the next section.

3.4 Building Pressure Coefficients

All building surface pressures are measured with respect to the static pressure of the water flume at the axial location of the pressure orifice. As was described in section 3.1, this is equivalent to noting the water surface elevation at the specified axial location. Usually the water surface of a flume will not decrease significantly. Nevertheless, a change in elevation of only 1 mm will lead to significant error in building pressure measurement. Hence, it is recommended that all building pressures be obtained as a difference from the flume wall static pressure. This has several benefits;

1. Any adjustment of the water level will be noted by the flume wall static pressure.
2. The static pressure cannot be measured as accurately by a level gauge as it can by an electronic pressure transducer.
3. The measurement of a pressure differential consisting of the flume wall static pressure and a building surface pressure reduces the net pressure acting on the transducer diaphragm to their differential.

As previously discussed, it is not practical to select pressure transducers that can withstand the full pressure of the flume acting on one side of the sensing element. Hence, fail safe switching of scanivalve leads must be ensured so that the pressure transducer only senses pressure differentials at all times.

The dimensionless pressure coefficient C_p is defined as;

$$C_p = \frac{(P_{building} - P_{static})}{0.5\rho \overline{U}^2_{ref}} \tag{5}$$

Where;

$\overline{U}_{ref}$ = the mean velocity at the reference elevation,

$P_{building}$ = one of the measured building wall pressures,

P_{static} = the flume wall static pressure at the axial location of the building pressure orifice.

Values of $-6.0 \leq C_p \leq 1.0$ can be expected for buildings subjected to eddy suction through to frontal wind conditions (Standen *et al.*[6]).

When determining the pressure tap locations considerable care must be exercised to ensure that an adequate distribution and number are provided to be able to extract meaningful surface pressure contours from the data. As many pressure taps as possible should be located near corners and other regions of rapid adjustment of surface pressure. Often is is necessary to include additional taps in regions that, prior to testing, are suspected of exhibiting large changes of pressure coefficients.

This is particularly true of corner regions since they exhibit pressure coefficients of $0.0 \leq C_p \leq 1.0$ for frontal winds in unshielded locations, and values of $-6.0 \leq C_p \leq 0.0$ in corner eddy conditions. The pressure coefficient are extremely dependent upon building geometry, approach wind direction, and the proximity of other buildings. Even the concept of flow symmetry must be abandoned for pressure coefficient measurement, since the two sides of a symmetrical building will experience different wall pressure patterns if nearby building blockages or wakes exist and when for many of the possible flow directions.

3.5 Pressure Measurement Time

The measurement time for surface pressures and wind velocities is dependent upon two parameters:

1. The response time to reach steady state of the pressure transducer, associated pressure tubing, and pressure orifices when the scanivalve switches to the associated ports.
2. After steady state is reached the sampling time required to obtain a statistically valid mean value of the pressure signal in the presence of pressure fluctuations caused by;
    (a) turbulence or eddies in the flow inherent to the particular approach boundary layer and model induced flow disturbances,
    (b) and any ripples or waves on the water surface caused by structural vibrations, poor inlet flow to the flume, pump turbulence etc..

Fig. 5 displays the measurement time for a typical signal. It consists initially of the response time to reach steady state and then the sampling time required to obtain a statistically valid mean pressure. Software is required to control the measurement time to ensure that a valid mean pressure is obtained. It is possible to reduce the response time to steady state by;

1. Reducing the length and volume of pressure tubing leading from the pressure orifices to the scanivalve.
2. Selecting a pressure transducer with as small a change in volume as possible for change of pressure.
3. Grouping pressure taps such that similar pressures are read sequentially by the scanivalve and pressure transducer.

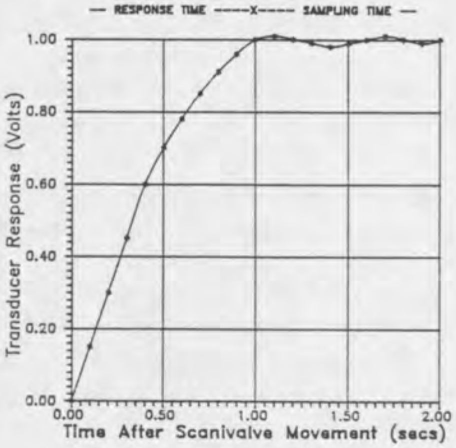


Figure 5. A representation of the measurement time required to obtain a valid mean value of pressure after port switching by a scanivalve. The measurement time consists of the response time of the system and the sampling time to obtain statistically valid data.

It is possible to remove some of the sampling time required to obtain a mean pressure by eliminating surface waves from the flume through the correct application of flow smoothing screens, pump vibration isolation, and good head box and constant head tank design. In practice if surface waves are eliminated, then the sampling time is reduced by increased flume velocities. This is due to the increased frequencies of any model induced flow eddies and the greater accuracy of measurement of the larger pressure signals created by the higher velocities.

4.0 AUTOMATION OF DATA ACQUISITION

4.1 Automation of Pressure Measurements

The measurement of a large number of building pressures, pedestrian level wind data and boundary layer velocities has been automated by the authors. All of these data are read as pressures referenced to a reference static pressure by a pressure transducer and a data logger. The data are required to meet statistical tests to ensure that steady state has been achieved and that the mean value of the pressure has been measured. The data are then transferred to a microcomputer that operates under MS-DOS and is programmed in Microsoft QuickBASIC 4.0 (Fig. 2 and Photograph 4). The data are arranged in arrays by QuickBASIC and are loaded in to the electronic spreadsheet SuperCalc 4.0 for report generation and data plotting. All data manipulation is conducted via batch files and macro programs written for SuperCalc 4.0, and hence, can be assigned to technical personnel for data reduction, thereby freeing the engineer who wrote the programs to pursue other tasks.

The automation of pressure data reduction and plotting has led to a significant saving of time and effort, to say nothing of the time saved in error checking. Typically, after a model test, the data are plotted and examined before the next test is started to ensure that valid results have been obtained.

Finally, the use of a soon to be installed automated turntable will permit unattended testing of models during evenings and overnight. This feature is looked forward to with anticipation, since it will significantly increase the productivity of the water flume test facility.

4.2 Automation of Report Preparation

Data obtained from snow accumulation, pedestrian wind, and building pressure studies will be stored on the hard disk of the microcomputer. The data when imported into SuperCalc 4 by batch files and macros is ready for report quality graph production and final report preparation.

The inclusion of graphical data into the final report is now directly possible with the advent of such laser printer and graphics input supporting word processors as WordPerfect 5.0. The final report need only be minutes removed from the final data acquisition from the water flume test facility.

5.0 CONCLUSIONS

An open channel water flume has been shown to be equal to a wind tunnel for building pressure and pedestrian level wind studies, when instrumented with appropriate pressure taps and velocity sensors. In addition, a water flume permits better flow visualization and snow simulation than does air flow in a wind tunnel.

The application of fundamental fluid mechanics principles, Reynolds number modelling, and automation of pressure measurements permits a water flume to obtain wind engineering data equal to or superior to that obtained in a wind tunnel. It has been shown that boundary layer development in a flume obeys the same principles as those developed for wind tunnels. It has also been shown that water flumes when compared to wind tunnels are more compact, less energy demanding, and are not influenced by day to day or building induced changes of atmospheric pressure.

The automation of an open channel water flume is readily achieved by using conventional data loggers, scanivalves, and support software. The subsequent reduction of data for interpretation and report preparation is direct and efficient.

Finally, the authors look forward to a soon to be implemented scheme to employ measurement techniques to obtain snow accumulation profiles via automated traversing gear, contour plotting software, and contour integration algorithms. Then, a water flume will be able to provide totally automated data acquisition of snow accumulation, building pressures, and pedestrian level winds. This level of engineering achievement should encourage a wide acceptance of water flumes by snow and wind engineers.

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