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VENTS, VENTILATION DRYING, AND PRESSURE MODERATION

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Executive Summary

Background

The orientation, size, and nature of vents in screened exterior wall systems are important to wall performance because these characteristics affect venting, ventilation and pressure moderation. The ventilation of screened wall systems has received very little attention in Canadian building research. With funding from CMHC's External Research Program, the Building Engineering Group at the University of Waterloo undertook an experimental and theoretical study of vents and venting in screened walls. The **objective** of this study was to define the problems and potentials, develop upper and lower bounds of likely performance, and provide some theory and complementary experimental measurements as a precursor to future more detailed and directed studies. The scope of the study extended to all screened and vented exterior wall systems. Masonry veneer walls were of special interest because of their wide use and the special importance of ventilation to this type of wall.

Literature Review

Codes, standards and previous research relating to vents and ventilation in wall systems have been reviewed and summarized. European codes are generally more specific regarding the size and location of vents and require much higher vent areas than North American code requirements. Most of the relevant wall cavity ventilation research has been conducted in Europe. A review of the limited available literature which reports the field measurement of ventilation indicated that very well vented wall systems (vent areas of more than 1% of wall area) typically experienced flow velocities of 0.1 to 0.2 m/s. Despite the extensive use of ventilated cladding systems in Europe, the benefits, drawbacks, and mechanics of ventilation flow have not been clearly defined. Moreover, very little work has been done on masonry veneer wall systems.

Theoretical Considerations

Ventilating the space behind the cladding with outdoor air offers two major benefits:

- relatively dry outside air flow allows evaporative drying of the inside face of the cladding and outside face of the inner wythe, and
- water vapour diffusing through the inner wythe can bypasses the vapour diffusion resistance of the cladding and be carried outside.

The heat capacity of air is so limited that unless there are very high air flow, little heat can be carried out of the air space. For most of the time in most enclosure walls, the effect of ventilation will not affect the insulation value of the air space. Very small air flows can, however, transport significant quantities of moisture. The cavity in many walls is usually warmer and contains more moisture than the outdoor air. Therefore, even small ventilation flows have the potential to remove moisture.

Forces Driving Ventilation Flow

Ventilation is driven by a combination of wind pressures, thermal buoyancy and moisture buoyancy. It can be shown that temperature and wind pumping in wall cavities with only one vent opening will provide less than 1% as much air flow as the flow generated between two vents. The provision of vent openings at both the top and bottom of the cavity will generally allow the most ventilation. The study therefore concentrated on wall systems with vents or slots placed at the top and bottom of the cavity.

Wind pressure is the most important force driving ventilation flow. For most Canadian locations, the wind blows 90% of the time, but the average wind velocity is generally quite low (3-4 m/s at 10 m above grade). Low-rise houses will often be protected from wind (by neighbouring buildings and by their location near the ground) but mid- and high-rise buildings will often be fully exposed to the wind. Average wind pressures driving ventilation on low-rise buildings can be expected to be in the order of 1 Pascal, but there the average will fall in a wide range between 0.1 and 10 Pascals, depending on the geometry and size of the building, the location and distance between vents, and wind speed and wind direction.

Increasing temperature and water vapour content decrease the density of air; these changes in density generate buoyancy effects that can drive ventilation air flow. Temperature and moisture buoyancy are likely to be of almost equal significance. Because of solar heating and outward heat flow in winter, the cavity of typical walls can be expected to be an average 3 to 5 °C warmer than ambient over the entire year. Daily variations of 15 to 20°C above ambient can be expected. Pressures in the order of 1 Pascal can be expected due to the combined effects of moisture and temperature buoyancy. These pressures can, in mathematical terms, be relatively accurately defined given some knowledge of the temperature and moisture conditions within the cavity.

Ventilation Flow Rates

A review of the literature of air flow through cavities was also conducted. The roughness of the cavity sides is not very important in practical walls, but the partial blockage of the cavity by mortar fins, strapping, bulging insulation, displaced building paper, etc. can be very important; large cavity widths are suggested as a means to overcome these potential blockages. In wall systems with discrete vents (e.g. masonry veneers), the vents impose the large majority of the resistance to air flow. Therefore, increasing the vent area will have a direct improvement on the air flow through the cavity. European open-jointed panel cladding systems will generally permit an order of magnitude more air flow than typical masonry veneer wall systems because of their large vent areas and clear cavities.

The flow generated by typical driving pressures (0.5 to 2 Pascals) can be expected to be in the order of 0.05 to 0.5 litres per second per m^2 of cladding depending on the vent area and the depth and degree of blockage of the cavity.

Ventilation Drying Rates

Outside air almost always has a lower vapour pressure than the air in the cavity, especially if the sides of the cavity are wet. Therefore, ventilation air flow can remove moisture from both the back of the cladding and the outer surface of the inner wythe by evaporation. Thus, ventilation drying can increase the drying potential of a wall system. Drying the inside of a brickwork veneer from the outside face only can be a slow process. Saturated materials in the inner wythe can also be dried much more quickly with the aid of ventilation air flow than by diffusion through the cladding.

Evaporation and drying due to air flow were also examined with the aid of available physics. It was found that air flows of the order of 0.05 to 0.5 litres per second per m^2 of cladding can remove from 10 to 1000 g of moisture per day per m^2 from behind the screen, depending on the exterior environment. Ventilation drying will be about ten times greater in July than January.

Cladding materials such as brick, concrete, natural stone, vinyl, metal and wood have a low water vapour permeance. In fact, all of these materials are sufficiently vapour impermeable to be classed as Type 2 vapour barriers or better. The drying of wet parts of an assembly will be greatly restricted by these claddings because evaporated moisture cannot diffuse through the cladding. Condensation can be expected to occur on the inside face of such cladding. However, it can be shown that exceptionally small ventilation rates ($0.1\ l / m^2 \cdot s$) will greatly increase the effective vapour permeance of otherwise vapour impermeable claddings. For claddings such as vinyl and steel, ventilation may be the a major contributor to their observed successful field performance. The reduction in vapour resistance due to ventilation air flow can be easily calculated using a concept, developed in the report, called equivalent permeance.

In some situations, excessive ventilation may cause wetting of the backside of cladding. Night-sky radiation can cause cooling of the cladding below ambient temperatures especially for thermally lightweight cladding (e.g. vinyl, metal). This can allow condensation on the cladding to occur. However, for claddings that store sufficient quantities of heat, the potential for ventilation-induced condensation is small because the temperature is almost always above ambient due to stored solar heat and outward heat flow. The influence of increasing vent areas on increased driving rain penetration also requires considerations.

Laboratory Vent Flow Tests

Airflow through vents under both static and dynamic pressures was studied in a series of laboratory experiments. Idealized vents (sharp-edged orifices), model head joints, and commercially available masonry veneer vent inserts were examined. It was found that all of the commercially available masonry veneer vent inserts that were tested greatly restricted flow. The flow through these inserts ranged from 1 to 15% of the flow through an open head joint.

Testing also showed that for steady or slowly-varying air-flow calculations, standard (10 x 65 x 90 mm deep) open head joints in masonry veneers can be considered to behave as orifices with a flow coefficient of 0.65 and a flow exponent of 0.55. Idealized orifices closely follow the power law, with a flow exponent of 0.5 and a flow coefficient of about 0.61.

In all cases, the flow under dynamically-varying pressure differences was higher than under static pressures but the actual flow could not be predicted using the standard orifice flow equations used for steady pressure differences. The velocity distribution that typically forms under steady pressure differences likely did not have sufficient time to form in the dynamic pressure tests and this resulted in the higher measured flows.

Field Pressure Measurements

Wind pressures have the greatest potential to drive ventilation flow, but the influence of wind speed, wind direction, and vent separation is difficult to quantify. To help assess the complicated interaction of these variables, the pressures on a rectangular low-rise building were monitored continuously for six weeks. The pressure difference between the vents in five different configurations was recorded every second. The wind speed and wind direction were also recorded.

A statistical analysis of the data indicated that ventilation pressures of 1 Pascal often occurred, but that the pressures were quite variable. Although wind direction plays an important role, even the leeward side of the building experienced significant ventilation pressures.

Conclusions and Recommendations

Ventilation, even small amounts, can provide significant benefits to wall performance, mostly by contributing to the removal of moisture from behind the screen. If unobstructed cavities and several strategically located large vents are provided in a screened wall, significant ventilation air flow can occur, even with the very small driving pressures that typically occur in service. The same measures will allow for the moderation of wind-induced pressure differences across the screen.

Laboratory testing of air flow through proprietary masonry vent inserts show that these inserts greatly reduce ventilation flow. The flow of air through vents driven by dynamic pressure variations is greater, sometimes significantly so, than when driven by a static pressure difference.

Designing new or the retro-fit of existing wall systems that encourage ventilation flow can greatly increase the drying potential of a wall assembly. In masonry veneer construction, it is recommended that minimum venting, i.e., an open head joint every 600 mm o.c. *at the top and* *bottom* of a 2.5 m high cavity or 0.2% of the wall area, should be provided. To achieve significant benefits from pressure moderation and ventilation drying, at least three times this area (0.6% of wall area) should be provided. To ensure clear cavities (which encourage good ventilation and allow drainage), the minimum width of the air space should be 30 mm, preferably a width of 40-50 mm should be provided.

Despite the benefits of ventilation flow, very little is known and it is recommended that a judicious mix of theoretical modelling, lab experiments, and field monitoring should be undertaken.

Résumé

Contexte

L'orientation, les dimensions et la nature des orifices de ventilation aménagés dans les écrans pare-pluie sont importantes pour la performance des murs, car ces caractéristiques agissent sur le mouvement de l'air, la ventilation et la modération de la pression. La ventilation des écrans pare-pluie a reçu très peu d'attention par les chercheurs en bâtiment canadiens. C'est ainsi que grâce à des fonds obtenus dans le cadre du Programme de subvention de recherche de la SCHL, le *Building Engineering Group* de l'université de Waterloo a entrepris une étude expérimentale et théorique des orifices de ventilation et du mouvement de l'air à l'intérieur des écrans pare-pluie. Cette étude avait pour **objectif** de définir les problèmes et les possibilités d'application, d'établir les limites supérieures et inférieures de la performance probable ainsi que de fournir une certaine théorie et des mesures expérimentales complémentaires devant servir de fondement à des études ultérieures plus poussées et plus circonscrites. L'étude a porté sur tous les types d'écrans pare-pluie et de murs extérieurs ventilés. Les placages de maçonnerie présentaient un intérêt particulier parce qu'ils sont très répandus et parce que la ventilation revêt une importance appréciable dans ce genre de mur.

Recherche documentaire

Nous avons étudié et résumé les codes, les normes et les recherches antérieures touchant aux orifices de ventilation et à la ventilation des murs. Les codes européens sont généralement plus précis en ce qui concerne les dimensions et l'emplacement des orifices de ventilation et exigent de plus grandes surfaces de ventilation que les codes nord-américains. La plupart de la recherche pertinente portant sur la ventilation des cavités murales a été menée en Europe. Un examen de la documentation limitée faisant état de mesures de ventilation prises sur le terrain révèle que les murs très bien ventilés (surface de ventilation supérieure à 1 % de la surface murale) présentent des débits de 0,1 à 0,2 m/s. Toutefois, en dépit de l'utilisation très répandue, en Europe, des parements ventilés, leurs avantages, leurs inconvénients et la mécanique de la ventilation n'ont pas été clairement définis. En outre, les placages de maçonnerie ont été très peu étudiés.

Aspects théoriques

Le fait de ventiler avec de l'air extérieur la cavité qui se trouve derrière le parement comporte deux avantages importants :

- la circulation d'air extérieur relativement sec permet l'assèchement par évaporation de la face intérieure du parement et de la face extérieure de la paroi interne;
- la vapeur d'eau diffusée à travers la paroi interne peut être évacuée à l'extérieur malgré la résistance du parement à la diffusion de la vapeur.

La capacité thermique de l'air est si limitée qu'à moins d'un débit d'air très élevé, il ne peut y avoir une grande déperdition de chaleur hors de la cavité. La plupart du temps, et pour la plupart des écrans pare-pluie, la ventilation n'a aucun effet sur le degré d'isolation thermique de la lame d'air.

De très faibles débits d'air peuvent, néanmoins, transporter d'importantes quantités d'humidité. Pour bien des murs, la cavité est habituellement plus chaude et renferme plus d'humidité que l'air extérieur. Par conséquent, même de faibles débits de ventilation peuvent extraire de l'humidité.

Forces produisant la ventilation

La ventilation se produit grâce à l'effet conjugué des pressions du vent, de la poussée thermique et de la poussée de l'humidité. On peut démontrer que la température et le vent qui s'infiltre dans les cavités de murs pourvus d'un seul orifice de ventilation produisent un débit d'air équivalent à moins de 1 % de celui qu'ils créent entre deux orifices. C'est pourquoi l'aménagement d'orifices de ventilation en partie supérieure et inférieure de la cavité permettra généralement une ventilation optimale. L'étude a donc porté uniquement sur les murs dotés d'orifices de ventilation ou de chantepleures au haut et au bas de la cavité.

La pression du vent est la force la plus importante qui favorise la ventilation. Au Canada, en général, le vent souffle 90 % du temps, mais sa vitesse moyenne est habituellement très faible (entre 3 et 4 m/s, à 10 m au-dessus du sol). Les maisons de faible hauteur sont souvent protégées du vent (soit par les bâtiments voisins ou par le fait qu'elles sont près du sol), mais les bâtiments de moyenne et de grande hauteur sont souvent entièrement exposés au vent. Les pressions du vent moyennes qui assurent la ventilation des bâtiments de faible hauteur sont sans doute de l'ordre de 1 pascal, mais la moyenne varie largement dans une gamme comprise entre 0,1 pascal et 10 pascals, selon la géométrie et la taille du bâtiment, son emplacement et la distance entre les orifices de ventilation, la vitesse du vent et sa direction.

L'élévation de la température et l'augmentation de la teneur en vapeur eau diminuent la masse volumique de l'air. Ces variations de masse volumique produisent des poussées qui peuvent entraîner un mouvement d'air de ventilation. La poussée de la température et de l'humidité revêtent probablement une importance presque équivalente. En raison de la chaleur du soleil et de l'exfiltration de chaleur en hiver, on peut prévoir que la cavité d'un mur moyen soit de quelque 3 à 5 °C plus chaude que la température ambiante pour l'année entière. Des variations quotidiennes de 15 à 20 °C au-dessus de la température ambiante sont probables. Des pressions de l'ordre de 1 pascal sont à prévoir en raison de l'effet conjugué de la poussée de la température et de l'humidité. Ces pressions peuvent, en termes mathématiques, être définies assez précisément quand on connaît les conditions de température et d'humidité à l'intérieur de la cavité.

Débits de ventilation

Nous avons également examiné la documentation existant sur le mouvement d'air dans les cavités. La rugosité des parois à l'intérieur des cavités n'est pas très importante dans la réalisation proprement dite des murs, mais l'obturation partielle de la cavité par les bavures de mortier, les fourrures, l'isolant saillant, le papier de construction déplacé, etc. peut revêtir une très grande importance. Nous suggérons donc d'aménager de larges cavités pour prévenir d'éventuelles obturations. Dans les murs à orifices de ventilation distincts (placages de maçonnerie, p. ex.), ce sont les orifices qui opposent le plus de résistance au mouvement de l'air. C'est pourquoi en augmentant la surface de ventilation, on obtient une amélioration directe du mouvement de l'air dans la cavité. Les panneaux de parement européens à joint ouvert permettent généralement un meilleur mouvement d'air (par un ordre de grandeur de 1) que les placages de maçonnerie traditionnels en raison de leur grande surface de ventilation et de leurs cavités libres.

Le mouvement d'air créé par les écarts de pression (de 0,5 à 2 pascals) peuvent être de l'ordre de 0,05 à 0,5 litre par seconde par m² de parement selon la surface de ventilation, la profondeur de la cavité et le degré d'obstruction de celle-ci.

Taux d'assèchement par ventilation

L'air extérieur a presque toujours une tension de vapeur plus faible que l'air de la cavité, surtout si les parois de la cavité sont humides. Par conséquent, un mouvement d'air de ventilation peut enlever l'humidité, par évaporation, tant de la face intérieure du parement que de la surface extérieure de la paroi interne. L'assèchement par ventilation peut donc accroître le potentiel de séchage d'un mur. Assécher l'intérieur d'un placage de brique à partir de la face extérieure ne peut qu'être lent. Les matériaux saturés dans la paroi interne peuvent également être asséchés plus rapidement par ventilation que par diffusion à travers le parement.

Nous avons aussi examiné l'évaporation et l'assèchement par mouvement d'air au moyen des données physiques disponibles. Nous avons constaté que des mouvements d'air de l'ordre de 0,05 à 0,5 litre par seconde par m² de parement peuvent éliminer de l'arrière de l'écran de 10 à 1 000 g d'humidité par jour par m², selon la nature du milieu extérieur. L'assèchement par ventilation est environ 10 fois supérieur en juillet par rapport à janvier.

Les matériaux de parement comme la brique, le béton, la pierre naturelle, le vinyle, le métal et le bois ont une faible perméance à la vapeur d'eau. En fait, tous ces matériaux sont suffisamment imperméables à la vapeur pour recevoir un classement «Type 2» ou mieux comme pare-vapeur. Ces parements entravent grandement l'assèchement des parties humides d'un assemblage parce que l'humidité qui s'évapore ne peut pas s'échapper par le parement. Il faut donc s'attendre à la formation de condensation sur la face intérieure de ce genre de parement. Or, on peut démontrer qu'un débit de ventilation exceptionnellement faible (0,1 L/m².s) peut augmenter sensiblement la perméance à la vapeur effective de parements normalement imperméables à la vapeur. Dans le cas de parements comme le vinyle et l'acier, la ventilation peut constituer le facteur le plus important de leur bonne performance en service. La réduction de la résistance à la vapeur grâce à la ventilation peut facilement être calculée au moyen d'un concept, expliqué dans le rapport, que nous appelons la perméance équivalente.

Dans certaines situations, une ventilation excessive peut entraîner le mouillage de la face intérieure du parement. Le rayonnement lumineux du ciel nocturne peut refroidir le parement à une température inférieure à la température ambiante, surtout en ce qui concerne les parements légers (comme le vinyle et le métal). Ce phénomène peut se traduire par la formation de condensation sur le parement. Toutefois, dans le cas des parements qui emmagasinent suffisamment de chaleur, la possibilité que de la condensation se forme à cause de la ventilation est mince puisque la température est presque toujours supérieure à la température ambiante en raison de l'accumulation de chaleur solaire et de l'exfiltration de chaleur. Il faut également tenir compte du fait qu'en augmentant la surface de ventilation, on risque de favoriser une infiltration accrue de la pluie poussée par le vent.

Essais en laboratoire du passage de l'air dans les orifices de ventilation

Nous avons étudié le passage de l'air, par pression statique et dynamique, dans les orifices de ventilation lors d'une série d'expériences en laboratoire. Nous avons pour ce faire utilisé des orifices idéaux (à rebords aigus), des joints verticaux modèles ainsi que des pièces préfabriquées, vendues dans le commerce, à encastrer dans les orifices de ventilation des placages de maçonnerie. Nous avons découvert que toutes les pièces préfabriquées à encastrer étudiées entravent de beaucoup le passage de l'air. Il s'est avéré que ces pièces laissent passer de 1 à 15 % de la quantité d'air qui passe par les joints verticaux ouverts.

Les essais ont également démontré que pour les calculs de mouvements d'air constants ou à variation lente, les joints verticaux ouverts standards (10 x 65 x 90 mm) ménagés dans les placages de maçonnerie peuvent être considérés comme ayant un comportement similaire à celui d'orifices possédant un coefficient de débit de 0,65 et un exposant de débit de 0,55. Les orifices idéaux suivent de près la loi de puissance [$Q = Cd \bullet A \bullet \left(\frac{2 \bullet \Delta P}{p} \right)$], présentant un exposant de débit de 0,5 et un coefficient de débit d'environ 0,61.

Dans tous les cas, le débit soumis à des écarts de pression à variation dynamique était plus élevé que lorsqu'il était soumis à des pressions statiques. Cependant, le débit réel n'a pas pu être prévu au moyen des équations standards de débit des orifices utilisées pour déterminer les différences de pression constantes. La répartition de vitesses qui se produit habituellement à des différences de pression constantes n'a probablement pas eu le temps de se réaliser lors des essais de pression dynamique et les débits mesurés ont donc été plus élevés.

Mesures de la pression sur le terrain

Les pressions du vent risquent le plus de susciter la ventilation, mais l'effet de la vitesse, de la direction et de la séparation du vent est difficile à quantifier. C'est ainsi que pour évaluer les interactions complexes de ces variables, nous avons mesuré en continu les pressions subies par un bâtiment rectangulaire de faible hauteur pendant six semaines. Nous avons enregistré à chaque seconde l'écart de pression entre des orifices de cinq configurations différentes et nous avons mesuré la vitesse et la direction du vent.

Une analyse statistique des données a révélé que des pressions de ventilation de 1 pascal étaient fréquentes, mais que les pressions étaient très variables. Bien que la direction du vent joue un rôle important, même le côté sous le vent du bâtiment a subi d'importantes pressions de ventilation.

Conclusions et recommandations

La ventilation, même très faible, peut comporter d'importants avantages pour la performance des murs, principalement en contribuant à évacuer l'humidité emprisonnée derrière l'écran pare-pluie. Si l'on aménage une cavité exempte d'obstructions pour un écran pare-pluie bénéficiant de plusieurs orifices de ventilation de bonne dimension placés à des endroits stratégiques, il est alors possible d'obtenir un important débit d'air de ventilation, même lorsque les écarts de pression sont légers, ce qui est souvent le cas en service. Les mêmes dispositions permettent de modérer l'effet des différences de pression causées par le vent sur toute la surface de l'écran.

Les essais en laboratoire menés sur des pièces préfabriquées à encastrer dans les orifices de ventilation montrent que ces produits réduisent considérablement le débit de ventilation. L'air poussé dans les orifices par les variations de pression dynamique a un débit plus élevé, parfois dans une très large mesure, que lorsqu'il est poussé par une différence de pression statique.

La conception de nouveaux murs ou la réfection de murs existants favorisant la ventilation peut accroître considérablement le potentiel d'assèchement d'un mur. Pour la construction de placages de maçonnerie, on suggère d'aménager un minimum d'orifices de ventilation, soit un joint vertical ouvert tous les 600 mm *en partie supérieure et inférieure* d'une cavité de 2,5 m de hauteur, c'est-à-dire 0,2 % de la surface murale. Pour bénéficier des avantages importants que représentent la modération de la pression et l'assèchement par ventilation, il faut prévoir une surface au moins trois fois supérieure (0,6 % de la surface murale). Pour faire en sorte que les cavités soient libres (ce qui favorise une bonne ventilation et permet le drainage), la cavité devrait avoir une largeur minimale de 30 mm et, de préférence, une largeur de 40 à 50 mm.

Malgré les avantages qu'offre la ventilation, on en sait très peu sur le sujet et nous recommandons de procéder à un judicieux mélange de modélisation expérimentale, d'expériences en laboratoire et d'essais en service.

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1. Introduction

1.1 Background

The orientation, size, and nature of the vents in screened exterior wall systems are important because these characteristics and properties affect three important wall functions: venting, ventilation, and screen pressure moderation. Venting and ventilation are both concerned with air movement into and out of the cavity behind the screen. Vents can therefore greatly affect the ability of a wall to both moderate wind pressure differences across the screen and to assist in removing water vapour (and perhaps heat) from the cavity.

1.2 Objective

The objective of this report is to explore the influence of vents on ventilation and pressure moderation by presenting the results of some experimentation, providing a summary of related research, and attempting to theoretically model the physical phenomena involved. The emphasis is on the vents and ventilation rather than on pressure moderation. The ventilation of screened wall systems has received very little attention in Canadian building research. This report attempts to define the problems and potentials, develop upper and lower bounds of likely performance, and provide some theory and measurements as a precursor to future more detailed studies.

1.3 Scope

The scope of the study extends to all screened and vented exterior wall systems. The focus is, however, restricted to air movement through the vents in the screen and the influence of this air movement on wall performance. Both idealized vents (orifices) as well as commercially available vent inserts are examined.

Masonry veneer walls are of special interest because of their wide use and the special importance of ventilation to this type of wall. Although vent holes are often also drain (weep) holes, drainage, as such, is not an issue in this study. Nevertheless, it should be emphasized that drainage is an absolutely essential attribute of any screened wall system.

The study was initiated with a grant from the External Research Program from CMHC. The work actually conducted is a little different from our initial proposal in two important ways:

(i) we have done much more experimentation on vent performance than originally planned, and

(ii) because of improvements in pressure measurement technology and the use and development of our own facilities, it was unnecessary to resort to commercial test facilities.

As a result, our experimental work has been much more extensive than originally planned. Experimental procedures and equipment, theoretical development and detailed calculations are not presented in this report, in the interest of brevity. Should there be any detailed technical questions, BEG will readily supply comprehensive internal documentation, experimental results, and theoretical calculations.

1.4 Approach

The report begins with a discussion of air flow through vents. The basic theory is introduced and previous research is reviewed. Experiments to measure vent performance under static and dynamic pressures are described and the results discussed.

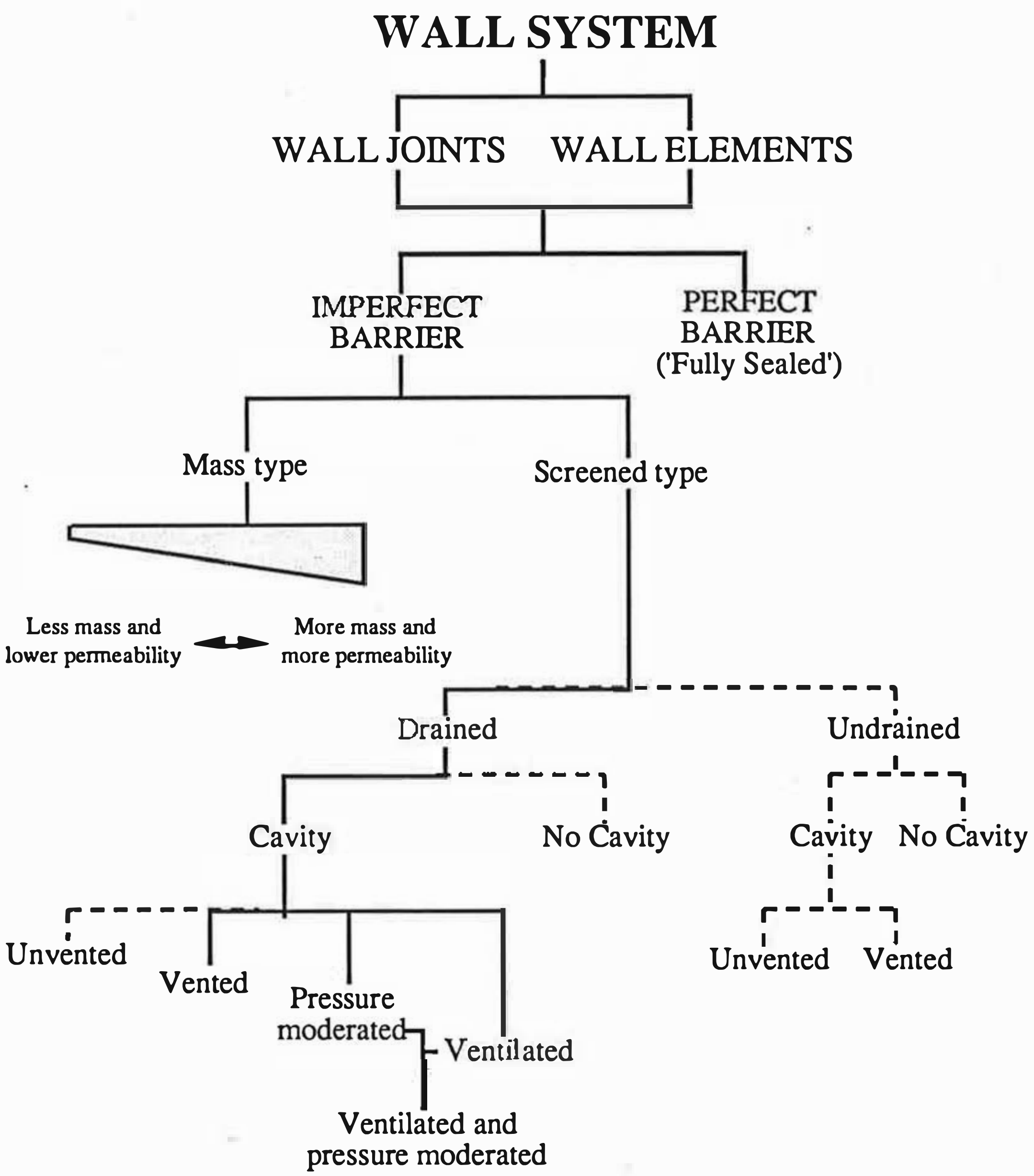
The forces which drive air through vents are then examined. A series of field measurements is described. The results and implications of these field measurements of driving forces on a low-rise building are presented and compared to other field and wind tunnel studies.

A summary of the mechanics of air flow through wall cavities and vents and the potential for ventilation drying are the topics of the next two chapters. Conclusions, recommendations for practice and research, and references are provided at the end of the report. An example of ventilation drying calculations and samples of the experimental results are contained in appendices.

1.5 Wall Systems: Definition and Categorization

To help place this study in context and to define the terms that will be used throughout this report, consider the wall categorization system presented in Figure 1.1. This categorization is based on the method by which the wall system actually controls rain penetration and is therefore independent of materials, building function, or design intent.

Walls are comprised of elements and the joints between these elements. Both wall elements and joints are dealt with in the same manner by the classification system. The primary classification is whether a wall is a **perfect barrier** (usually called face sealed) or an **imperfect barrier.** Because it is very difficult to build and maintain a perfect barrier wall, most walls are designed as, or perform as, imperfect barrier walls of either the mass type or screened type.



Notes:

The walls are categorized based on actual behaviour, not necessarily design intent.
For the purposes of this classification system, the following definitions are necessary:
Drained: the majority of the water that penetrates the screen is removed by gravity.
Cavity: a clear space or a filled space that facilitates gravity drainage and air flow and resists the lateral transfer of water (a capillary break).
Vented: allows some degree of water vapour diffusion and air mixing.
Ventilated: allows a significant flow of air largely to promote drying.
Pressure-moderated: an approach that moderates air pressure differences across the screen.

Figure 1.1: Wall Categorization System (by Rain Penetration Control)

Mass walls control rain penetration by absorbing and storing rain water which penetrates the exterior surface. This moisture is subsequently removed by evaporation (drying) before it reaches the inner surface of the wall.

Screened walls are also imperfect barrier type wall systems in that this design approach acknowledges that some rain water will penetrate the screen (which also resists wind, snow, solar radiation, etc.). Supplementary mechanisms, such as a capillary break, are usually employed to resist further inward movement of the water that penetrates the screen. Drainage is the most common and important mechanism by which any water that penetrates the screen is removed. The dashed lines in Figure 1.1 indicate that, while undesirable, undrained walls do exist.

Providing a **cavity** behind the screen provides a capillary break, a path for gravity drainage, and a path for air flow. A cavity is defined here as any clear unobstructed space, filled with a porous material or not, that fulfills these functions.

Given a cavity behind the screen, there are four major possible sub-classifications related to air movement and vents:

A **vented** wall allows some degree of water vapour diffusion and air mixing between the cavity and the exterior. Water that remains in the cavity, adhered by surface tension or absorbed by the materials that make up the sides of the cavity, cannot be removed by gravity drainage. Venting (and, to a greater degree, ventilation) provides another mechanism for the removal of water that does not drain from the cavity. Venting, or better still, ventilation, may also remove water vapour that has diffused outward from the inner wythes.

A **pressure moderated** wall moderates the pressure difference across the screen by the proper choice of vent size, number, and location and by delineating the cavity into stiff, airtight compartments. A relatively small volume of air needs to be exchanged to result in a significant amount of pressure moderation. Although such a wall is normally described as a pressure equalized rainscreen (PER) in Canada, pressure equalization is unlikely and the screen deals with more than rain -- hence the term "pressure moderated screened" (PMS) wall is preferred by the authors.

By increasing the flow of air into and through the cavity, a relatively large volume of water vapour can be transported from the cavity. Such a **ventilated** wall will assist the drying of both the inner wythe and the screen.

A wall can be both **pressure moderated and ventilated:** this is not only feasible but is to be preferred.

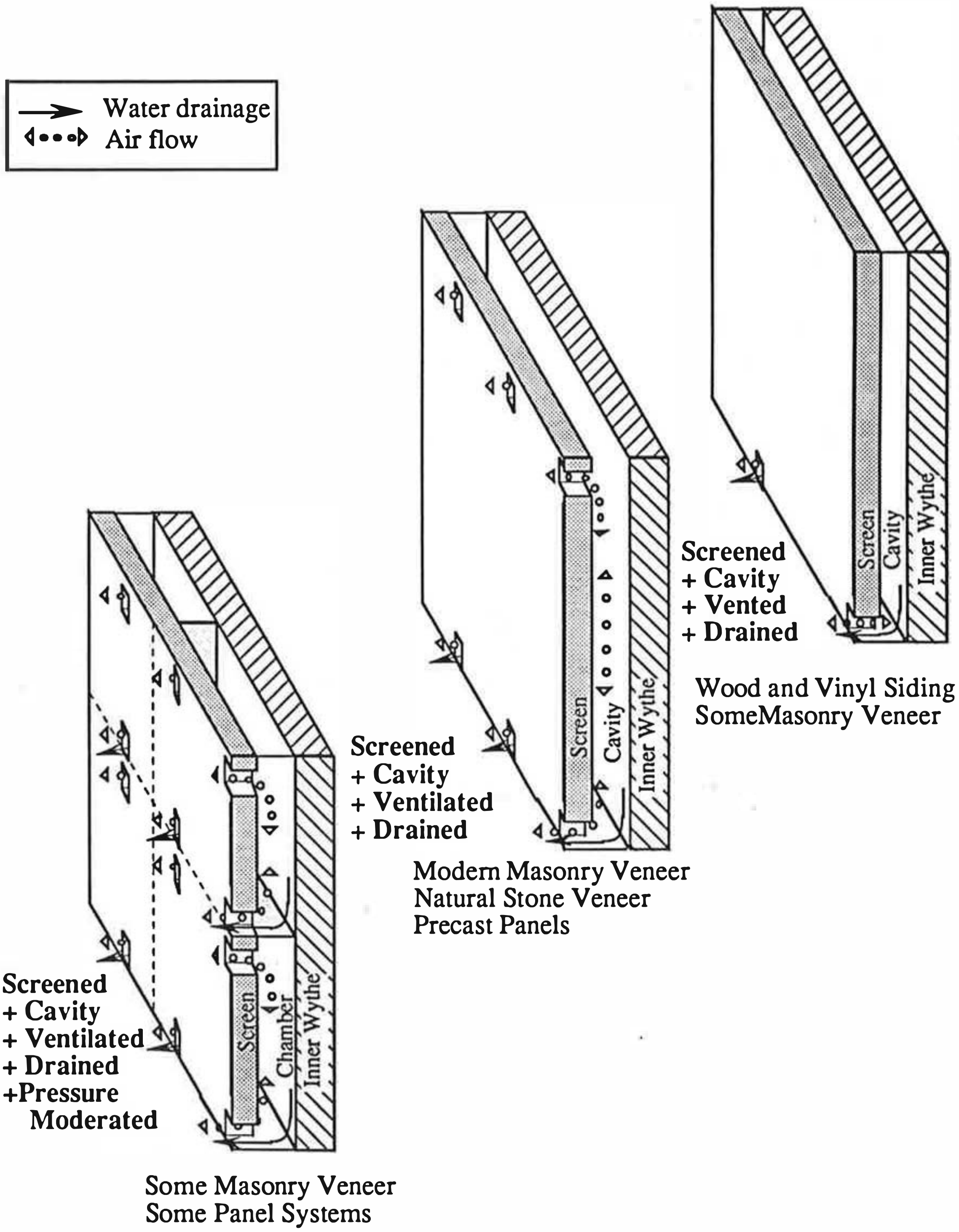


Figure 1.2: Example Wall Systems That Use Vents

1.6 Vented, Ventilated, and Pressure Moderated Wall Systems - A Review

Figure 1.2 presents idealized and simplified versions of exterior wall systems that incorporate vents. The common brick veneer wall with vented weep holes and vents at the base of the cavity is a practical example. There can be little question that this venting is both needed and beneficial since masonry veneer has a vapour permeance of about 45 ng/Pa·s·m^2 (masonry veneer would therefore qualify as a Type 2 vapour barrier).

By providing vent openings both at the top and bottom of such a brick veneer wall, the through-flow of air can be enhanced and the wall could be considered to be ventilated. Using open head joints at 600 mm spacing at both the top and bottom of the cavity provides a venting area of between 0.05 to 0.1% of the wall area (between 2 and 4% of the cavity cross-sectional area) in a typical 2.5 m high wall. However, the magnitude and nature of flow of air within such a space has, as far as we know, not been studied in North America.

1.6.1 European Wall Designs

For many years designers and builders in continental Europe have used ventilated wall systems; these are usually referred to as drained and back-ventilated wall systems [1] (Figure 1.3). This type of wall system has large vent areas and large clear cavities to encourage ventilation. The cavity height (often three to six storeys) and depth (30 to 50 mm is common) facilitates air flow driven either by stack pressure, by wind pressure, or by both. Vent areas are almost always provided in the form of full-width open slots or joints, 12 to 25 mm wide, of the order of 20 to 100% of the cross-sectional area of the cavity. Often venting of the cavity at the roof parapet is used to facilitate large suction pressures acting on the top vent independently of wind direction (much like a chimney); this ensures that wind effects and stack pressures drive air flow in the same direction. Naturally, drainage must be provided for and the cavity and fixings should be designed to ensure that very little, if any, water reaches the outer surface of the inner wythe. The potential performance improvements that such ventilation of this type may provide have been studied in Europe.

1.6.2 Canadian Wall Designs

A design strategy that is especially popular in Canada, even for brick veneer walls, is to attempt to provide a pressure equalized screened wall system (in reality a pressure moderated screened wall system is often constructed). Two characteristics of vents are critically important to the performance of PMS walls: the size of the individual vents and the distance between vents.

If the vents are too small, they may restrict the rapid flow of air into and out of compartments. For instance, large short-duration gust pressures may not be effectively moderated. Naturally, the vents must be large enough to resist the formation of a surface tension plug and small enough to avoid direct, wind-driven rain entry.

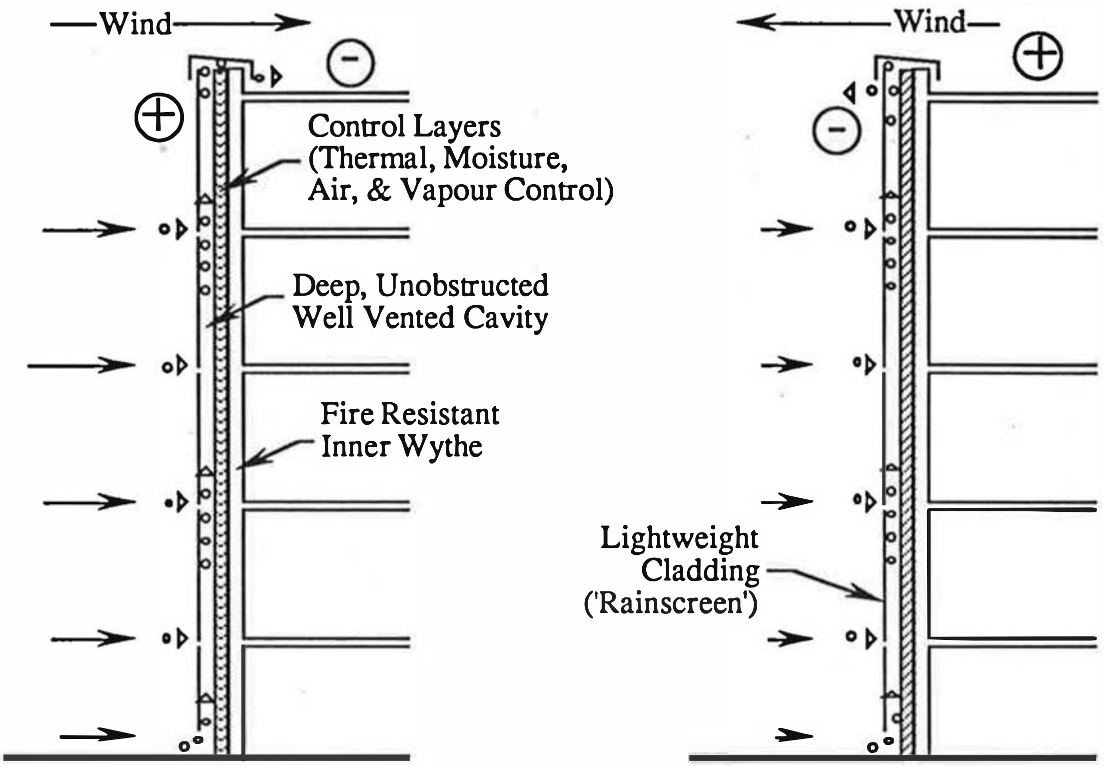


Figure 1.3: European Back-Ventilated Wall System

If the vents are spaced too far apart, spatial pressure variations in the wind may induce air flow through the cavity during rain events – if this through-flow is sufficiently fast, rain water may be entrained into the cavity. If the vents are grouped too close together spatial pressure variations that occur at some distance from the vent grouping will not be moderated because there is no means for air flow into the cavity, i.e. they may act in a similar manner to a single large vent.

A recent Canadian review of requirements for pressure moderated wall systems by Baskaran of the NRC/IRC [2], suggested vent areas of 1 to 2% of wall area. This translates into 100 to 200% of the cavity cross-sectional area for typical walls. Large vent areas are preferred in practice it is quite difficult to increase the vent area for some types of walls. Most existing pressure moderated walls designs provide a far lower degree of venting (for example, a typical vented brick veneer wall provides 0.1%).

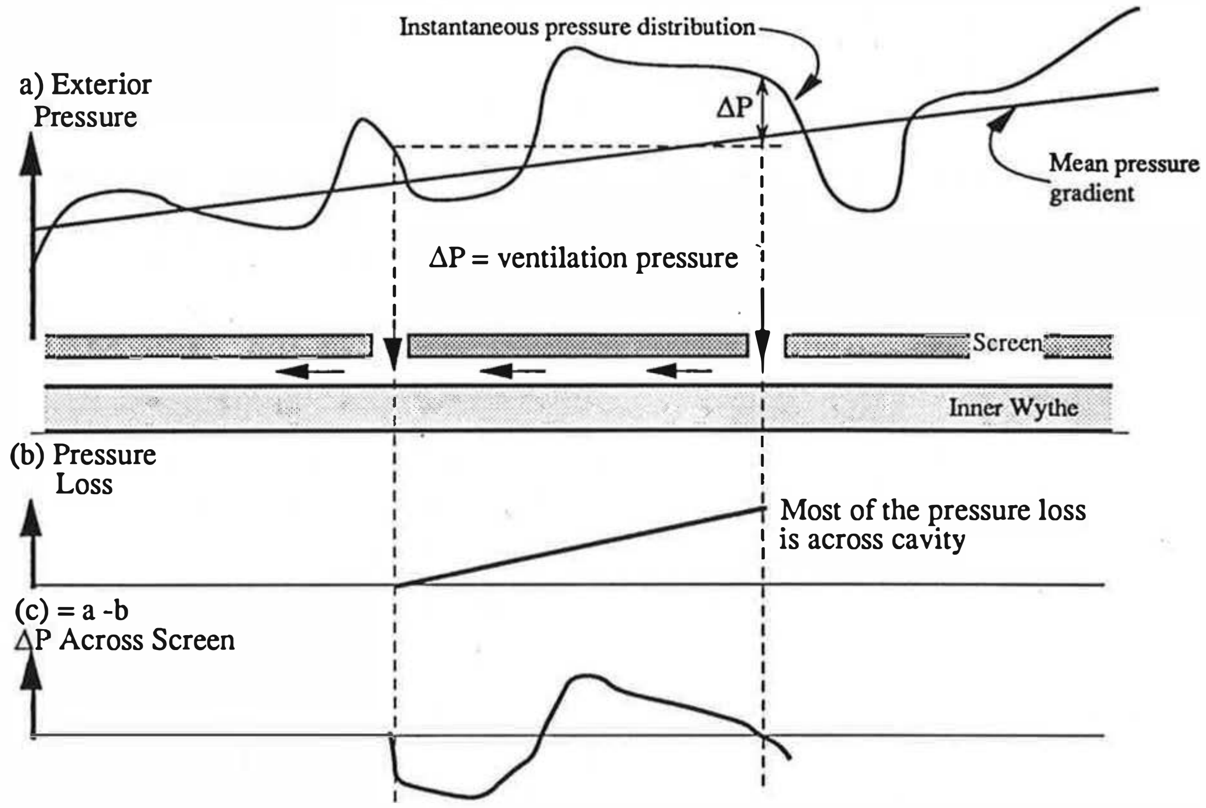
The use of a single, horizontal row of vents at the bottom of the chamber was also recommended by Baskaran. In effect a trade-off must be made between an acceptable mean flow of air through the cavity (greater spacing leads to greater flow) and greater peak wind loads across the screen (greater spacing leads to higher peak loads from spatially-small gusts). Years of field and wind-tunnel results and a relatively straightforward analysis of the spatial turbulence of wind pressures suggest that the greater the number and the more uniform the spatial distribution of vents across a compartment, the smaller the percentage of peak wind loads that will be taken by the screen.

Inculet [3], who conducted a theoretical and wind tunnel study of PMS wall systems, suggested vent areas of ≥ 2% of the wall area. Inculet also analytically confirmed that the greater the number and the more uniform the spatial distribution of vents across a compartment, the smaller the percentage of peak wind loads that will be taken by the screen.. Her analysis shows that a wall system with a slot at the top and bottom of a square compartment (similar to European back-ventilated wall systems) will reduce peak wind loads to 36% (a 64% reduction) of that on an unvented wall. By contrast, the use of two separate, discrete vents at the bottom with the same total venting area will only reduce the peak wind loads by 14% (i.e. 86% of the wind load acts on the screen).

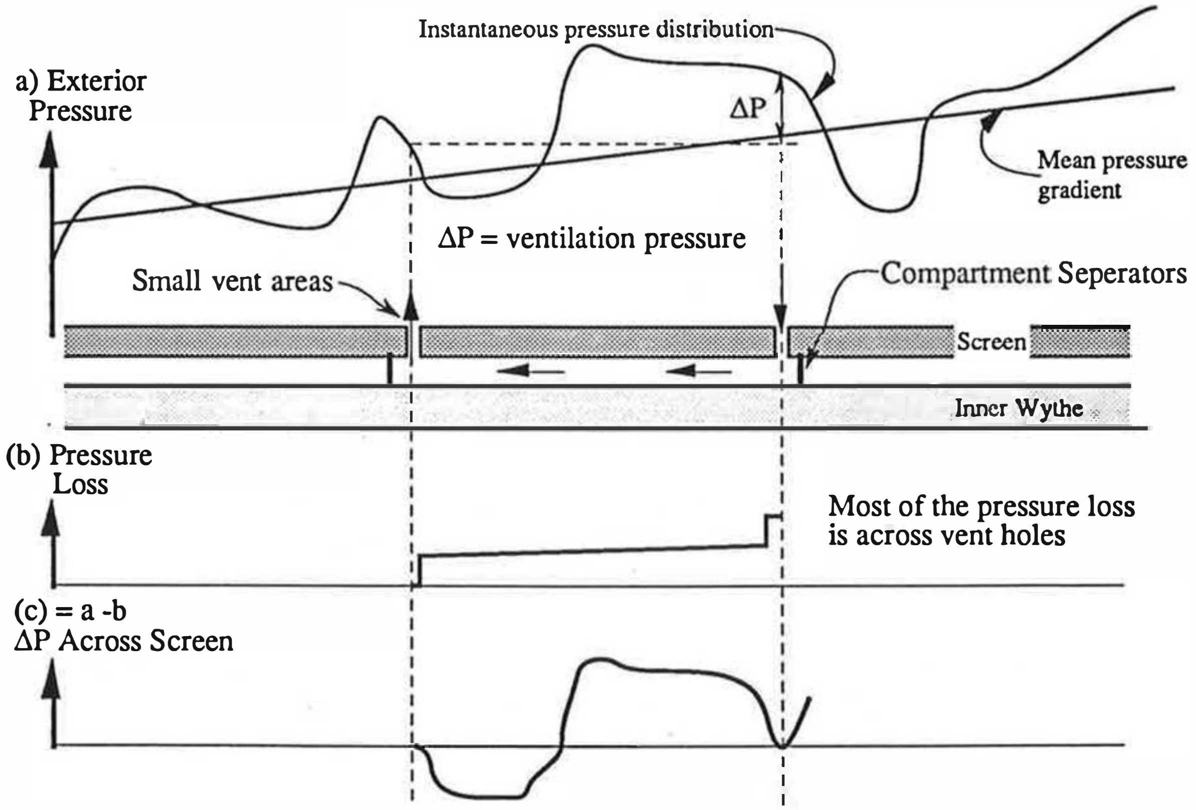
1.6.3 Differences Between Canadian and European Design Methodology

It must be noted that reality is very different from the simplistic ideal of the pressure equalized rainscreen; because of the spatial variations in wind pressure a PER wall with a single vent cannot pressure equalize. Multiple vents distributed over the area of the compartment can result in a spatially-averaged pressure response of the chamber with the lowest spatially-averaged average pressure difference across the screen. The spatial pressure variations will also result in some flow through vents exposed to different pressures.

It follows that ventilation and pressure moderation can co-exist, but the absolute spatial extent of compartments must be small enough to limit mean flows through the cavity. Figure 1.4 graphically presents the difference in performance between European and Canadian practice. This drawing presents a section (horizontal or vertical) through two wall systems with the similar dimensions. The European drained and back-ventilated wall system approach, with no compartment separators and large vent areas, results in the concentration of air flow restriction in the cavity but allows relatively easy flow through the vents. Thus, as shown in Figure 1.4, the pressure drop across the vents in the European walls is very small and the frictional loss of flow through the cavity is relatively large. The Canadian pressure equalized rainscreen approach, at least for most precast panels, stone and masonry veneers, provides compartment separators and smaller vent areas. This results in a concentration of flow resistance at the vents and relatively unhindered flow through the cavity. Hence, the largest pressure drop occurs across the vents. Note how this difference in flow resistance affects the resulting pressure difference across the screen – the European approach will result in better averaging of the pressure difference across the screen because the resistance to air flow is also spatially distributed.



European Back-Ventilated



Canadian Pressure Moderated Wall

Figure 1.4: Canadian Pressure Moderated Walls vs. European Back-Ventilated Walls

In effect, the Canadian approach uses physical airtight separators to compartmentalize the wall whereas the Europeans use the friction of air flow through the cavity to intrinsically compartmentalize. Two-stage joints are probably compartmentalized in a very similar way.

The proper choice of cavity size will also result in small compartments in the European practice. Recently, research published by Kramer and Gerhardt [4,5] based on field and wind tunnel studies, has begun to recognize the advantages of compartmentalizing using friction; it is now suggested that designers use smaller cavity depths (in the order of 12 mm) to increase friction and separators at the corners of buildings (where the gradients are so steep that friction alone cannot resist flow).

The advantage of the European approach is that ventilation (low volume air flow) is encouraged while maintaining a useful degree of pressure moderation. Under the small pressure gradients that exist most of the time, significant flow occurs behind the screen and allows trapped liquid moisture to evaporate and leave the wall system as water vapour.

A wall system can be designed to be both a ventilated and a PMS system. Ventilation drying obviously occurs only when both flow *and* inside and outside conditions are favourable e.g. when it is not raining and when there is some wind i.e., most of the time. Pressure moderation assists in the control of rain penetration only under conditions of driving rain on the windward side, i.e., rarely and never when ventilation drying could occur (although ventilation may occur).

1.7 Codes and Regulations

Although building codes and regulations may prescribe minimum values for ventilation flow or venting area for roofs and crawl spaces, rules for walls are rarely codified. The 1990 National Building Code of Canada (5.2.1.2.(1)) requires that where a layer outside the layer with the major thermal resistance significantly resists water vapour flow :

> *an air space ventilated to the outside or other method of equal effectiveness shall be provided for removing water vapour that may pass from the high vapour pressure side through the material with the major thermal resistance.*

This clause obviously applies to most screens – masonry, vinyl and wood siding, and sheet metal all have low vapour permeance ratings – and a vented air space is provided in most wall assemblies designed with these sidings.

The Canadian masonry construction standard (CAN3-A371-M84) requires (§ 5.12.1) that weepholes with an area of at least 70 mm^2 every 600 mm be provided at the base of every masonry veneer wall. This amounts to a vent area of 0.005% of wall area for a 2.4 m high wall and 0.002% for a 5 m high wall. The same clause adds, in a note, that:

> *Venting is often required in conjunction with weepholes to permit cavity walls and veneer walls to function properly.*

The new American masonry standard ACI 530-95/ASCE-95/TMS 402-95 Building Code Requirements for Masonry Structures contains a new chapter on masonry veneers. Clauses 12.8.3, 12.9.4, and 12.10.2 require a minimum 1 inch (25.4 mm) air space; this requirement is provided to ensure sufficient drainage, not ventilation. There is no minimum requirement for venting. Clause 12.2.2 requires that weepholes have a minimum dimension of 3/16 inch (5 mm) and be spaced less than 33 inches (825 mm) on center.

The Brick Institute of America's Technical Note # 27 [6] provides widely respected advice on brick masonry screened walls. It suggests that a minimum cavity depth of 50 mm and vent openings at the top and bottom be provided. Although there is no mention of a minimum absolute venting area, the Note states that open head joints at a maximum of 600 mm o.c. at the top and bottom of the cavity are acceptable (a vent area of less than 0.1 %) as are 10 mm diameter tubes at 400 mm o.c. (a vent area of less than 0.008%).

Other building codes, for example the German DIN standard, more precisely prescribe the measures required to ensure that some ventilation occurs. The masonry design standard, DIN 1053, requires in Clause 8.4.3.2 (double wythe masonry with air space) an air space at least 40 mm deep and vent openings, top and bottom, with a minimum area of 7500 mm^2 per 20 m^2 of wall; this is approximately 0.375% of wall area. The code for stone and ceramic facade cladding panels, DIN 18 165, requires a minimum air space of 20 mm, and horizontal slots top and bottom with a vent area of between 1 and 3% of the wall area. The code for facade cladding in general, DIN 18 516, requires a minimum 20 mm air space and 5000 mm^2 of vent area per m length of wall, with no opening dimension less than 20 mm.

The moisture protection standard, DIN 4108, prescribes procedures, material and climate values to be used in the calculating the resistance of a building assembly to condensation and driving rain. Using a simple steady-state Glaser diffusion analysis, DIN 4108 requires the calculation of the condensation volume during 1440 h of cold weather and the subsequent evaporation during 2160 h of summer weather. The standard requires that the moisture content in the materials not exceed given values and that annual evaporation exceed annual condensation. Most natural stone claddings fail to meet these requirements because the vapour resistance of the cladding is quite high. By ventilating an air space behind the cladding, the code exempts the assembly from these requirements. DIN 4108 provides vapour permeance values for two classes of bricks: Klinker, with a value of between 20 to 40 ng/Pa·s·m^2 and Ziegel, with a value of 200 to 400 ng/Pa·s·m^2. The Klinker class of hard-burned bricks should not be used in brick veneer walls that do not meet the ventilation requirements of DIN 1053 Clause 8.4.3.2 (see above). DIN 4108 makes no provision for daily summer vapour reversals even though these are generally recognized as a significant wetting mechanism in the German literature.

In general, European codes are much more explicit and require significantly greater venting area and cavity depths than North American codes. North American designers and builders would undoubtedly benefit from more information about how much and what kind of venting to provide in walls. Code prescribed values could be considered as a means to this end but not until the benefits and drawbacks of ventilation are quantified and the performance proven in the field.

1.8 Previous Research

Almost all building-related vent and ventilation drying research found in a literature survey was conducted in Europe. Much of the available research focuses on drained and back-ventilated panel systems and does not consider ventilation of brick veneer walls.

Several comprehensive studies of ventilation mechanics have been of general assistance in this study. The German texts, *Belüftete Dach- und Wandkonstruktionen: Bauphysikalische Grundlagen des Wärme- and Feuchteschutzes* (Ventilated Roof and Wall Constructions: Building Physics Fundamentals for Heat and Moisture Protection) by K.W. Liersch [7] and *Praktische Bauphysik*, by G. Lohmeyer [8], and Chapter 2 of the Dutch text *Bouwfysica 1: Warme- en massatransport* (Building Physics 1: Heat and Mass Transport) by Hugo Hens [9] contain excellent background information of ventilation flow mechanics. These texts also indicate how important wall ventilation is considered to be in designing standard wall panel cladding in continental Europe. The design procedures presented in these texts focus on increasing ventilation flow in open-joint cladding systems. Little guidance is provided for a designer who wishes to quantify ventilation drying or use brick veneer as the cladding.

In Canada, **Guy and Stathopoulus** [10] conducted an analytical study of the effect of stack-effect-driven ventilation behind cladding. They reported that a cooling load reduction of 35% of the extreme design value could be achieved using a storey height of 2.4 m, a cavity of 30 to 40 mm, and a vent area of 100% of the cross-sectional area of the cavity. Halving the venting area reduced the savings to 29% and doubling the insulation value of the inner wythe at the same time cut the savings further, to 20%. Reducing the emissivities (from 0.9 to 0.4) and decreasing the venting area to 25% of the cavity area resulted in savings of as much as 50%. The effect of wind was not taken into account in their analysis. The cooling effect of ventilation in winter will, however, increase heating energy consumption.

The **Fraunhofer-Institut für Bauphysik** has conducted field monitoring of ventilation and drying effectiveness for different types of panel cladding. One project measured the ventilation velocity and air exchange rate behind asbestos cement and wood siding with various types of cavities and venting arrangements. The cladding was installed over initially wet, aerated concrete blockwork and the moisture content (and hence drying rate) of these blocks was monitored over a period of two years. A complementary project involved the field measurement of ventilation behind large cladding panels on a three-storey building. The research is recorded in two confidential research reports provided to BEG by the present Director of the Institut [11,12] but most of the conclusions can be found in reference [13]. Some of the important findings and conclusions are summarized below :

- The most important wall characteristics were found to be the size of the vent openings and the presence of an unobstructed cavity.
- The three most important forces affecting ventilation drying were found to be wind-induced pressure differences, solar-induced buoyancy (stack effect), and solar heating. Solar heating increased the air temperature of the cavity air and thus allowed the transport of a much larger volume of water vapour.
- Hourly average air velocities of 0.05 to 0.15 m/s were measured in the wall cavities when the windspeed was between 1 to 3 m/s. Wind direction influenced the ventilation air velocity more than windspeed did.
- Walls with non-airtight joints (e.g., slate, shingles) were also shown to be ventilated (using tracer gas techniques), albeit less than intentionally vented walls. The greater the number of joints and the leakier the joint, the more ventilated the cavity. The pumping action of the wind was postulated as the ventilation mechanism in these walls.
- It was observed that with sufficient ventilation, condensation on the backside of the cladding rarely occurred.
- The researchers drew the following conclusions: a clear cavity depth (i.e. accounting for tolerances and potential blockage) of 20 mm is generally sufficient for panel-type cladding; although a large vent area is not absolutely necessary for acceptable wall performance, it is a practical means of removing trapped moisture; ventilation is less important if the backup wall or cladding has a low vapour permeance, or if the cladding allows significant airflow through it.
- It was recommended that the cladding should always be left open at the bottom to allow drainage of the condensate on the backside of cladding; if one uses materials which are sensitive to moisture in the backup wall, it is important to ensure that no water bridges can occur; and the size of the upper and lower vent openings should be as large as possible, especially for backup walls which have high levels of built-in moisture.

The **Norwegian Building Research Institute** has measured the pressure gradient in an airspace behind vertical wood siding on a rotatable test house in Trondheim, Norway [14]. The objective of the project was to assess the cooling effect of air blowing across and through the fibrous insulation adjacent to the cavity. They found that a wind barrier (not an air barrier) is essential to reduce convective heat loss through low-density fibrous insulations. This work also showed that the mean pressure gradient behind the siding was a highly correlated with windspeed and wind direction. The influence of solar heating was not reported. Maximum pressure gradients in the cavity of almost 100 Pa/m were measured during storms with high wind speeds (about 30 m/s). Average pressure gradients for all wind directions for a mean windspeed of 3 m/s were found to be between 0.1 to 0.5 Pa/m.

Schwarz [15] instrumented an 18-storey apartment building in Hamburg, Germany, with a 1.25 m x 1.35 m open-jointed panel cladding system to measure the velocity of the air flow in the cavity. The researchers from the Institut für Bauphysik measured velocities of 0.2 to 0.6 m/s under a range of windspeeds of 0 to 5 m/s. They found little relationship between building height and cavity ventilation velocity. It was also found that although lower velocities in the cavity were measured for the lee side than the windward side, the velocity on the lee side was usually stable at around 0.2 m/s for the normal range of wind velocities. The air exchange rate was therefore several hundred exchanges per hour, and vapour diffusivity played a completely insignificant role in the transfer of vapour from inside to outside.

Akoestisch Advies Bureau Peutz & Associes BV [16], a Dutch consulting group, conducted both a theoretical and wind tunnel study of the potential for ventilation in an open-jointed, small-panel cladding product. Their analysis and measurements suggested that properly designed cladding products could, on average, have ventilation velocities of 0.5 to 3 m/s. For Dutch conditions, such large velocities would result in enough ventilation to ensure that condensation would not occur on the backside of panels for typical backup wall assemblies. The panel sizes examined ranged from 200 to 800 mm in height, were installed over a 20 mm cavity, and had full-length open joints 20 mm wide.

VENTILATION BEHIND MASONRY VENEERS.

Reports of ventilation drying studies in masonry veneer wall systems are more difficult to find, and the results tend to be much less conclusive.

Kenneth Sandin [17] of Lund University, Sweden, conducted what is perhaps the most extensive study of ventilation behind brick veneers. The work consisted of an extensive field study of different types of brick-veneer clad, wood-frame wall systems for the Swedish Byggforskningsrådet (Building Research Council). In his measurements of cavity air exchange rates, he found that open head joints at typical spacings did increase exchange rates compared to the rates achieved by drainage tubes. In typical weather conditions, air exchange rates of 0.3 to 8 per hour were measured. However, only when an entire brick was removed every 1200 mm were substantial ventilation rates of 3 to 25 changes per hour measured. Although wind was thought to be the primary ventilation mechanism, ventilation rates during periods when the cladding was warmer than the outside air were almost always higher than when the cladding was at the same temperature as the outside air. In other published work [18,19], he questioned the effectiveness of ventilation in a climate (similar to Canada) where ventilation drying might remove 3 kg of moisture per month and driving rain could deposit 20 to 50 kg/month.

The **Fraunhofer-Institut für Bauphysik** has also conducted field monitoring of the moisture content of brick veneers in walls with and without (the cavity was filled with insulation) an air space [20]. Over about two years, approximately 100 gravimetric measurements were made of several different walls assemblies built in accordance with DIN 1053. The authors concluded that the presence of an air space had no effect on the moisture content of the brick veneer.

The **German Institut für Ziegelforschung** (Institute for Brick Research) conducted a unique field study of the effect of ventilation on the drying of brickwork [21]. A test building was constructed (in Essen, Germany) with a 40 mm deep cavity and vented at the top by a 30 mm open joint under the eaves and at open head joints in the bottom course (every 250 mm). The average ventilation velocity measured was about 0.1 m/s for an average windspeed of 2.6 m/s. This ventilation velocity was deemed to be slow enough that the insulation value of the air space was not significantly affected and yet resulted in an average of 100 air exchanges per hour. Measurements of the moisture content of the brickwork immediately after construction showed that drying occurred faster on the cavity side than on the outside. Within three weeks the brickwork dropped from 12% moisture content by volume to about 1.5%. In a recent discussion, the research engineer indicated that the major obstacle to significant ventilation drying in brick veneer walls was mortar obstructions in the cavity. Specifying a 50 mm cavity and large venting areas would, in his opinion, achieve practical results similar to those obtained in the more controlled study.

The **Laboratorium voor Bouwfysica** in Belgium has conducted a series of field, laboratory, and theoretical studies of masonry cavity walls. In a summary report [22] the issue of ventilation behind brick veneers is addressed. It was shown that ventilation has practically no effect on the heat transmission values of the air space, but it is was also found to be difficult to quantify the benefit of ventilation to moisture removal rates. Although it is recommended that ventilation continue to be used in veneer walls with air spaces, the author then states that only drain openings are required in cavities filled with insulation because the ventilation rates would be very low in any case. This is also the approach taken in the German code DIN 1053.

There remains a serious lack of quantitative information of the effect of ventilation on wall performance. The present trend in Germany appears to be away from ventilation and toward more vapour diffusive claddings and paint systems. Little research is being conducted on ventilated-panel systems because it is believed by the research and building communities that following the present codes will result in satisfactory performance. The influence of ventilation on brick veneer walls is little understood and requires much more research before any conclusions can be drawn.

2. Vents and Orifice Flow

2.1 Vent Types

Vents for use in screened wall systems can be divided into three broad types (Figure 2.1) :

- **Small circular openings and rounded slots.** Some types of contact siding (vinyl), window frames, and curtain walls often use circular or oval openings of 3 to 6 mm in one dimension and 3 to 25 mm in the other. These vents are usually in a thin material (0.5 to 3 mm thick) such as aluminum, PVC, etc.

  Flow through circular, sharp-edged orifices has been extensively studied. Theoretically, the sharp-edged circular orifice is also the easiest to analyze and hence has been chosen as the behavioural datum for this work. Also, flow through non-circular orifices is often analyzed by considering an equivalent diameter circular orifice. Therefore, we have chosen to study a range of orifices with both sharp edges and square edges and have attempted to compare the results to existing theory and other published research. A variety of orifice sizes (from 1 mm Ø to > 22 mm Ø) in 3 mm thick plate have been studied. To test the applicability of the equivalent diameter circular orifice theory to brick vents, a 19 mm Ø x 90 mm long pipe was considered and compared to orifices in thin plate.

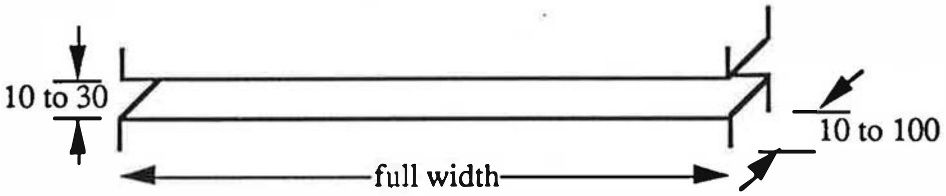
- **Deep rectangular openings.** These openings are used predominantly in masonry veneers. As such, the standard size is 10 wide by 60 to 80 mm high in elevation by 85 to 90 mm deep.

  Because walls screened with masonry veneer are very common, especially in residential building, the behaviour of relatively standard open head joints has been a focus of the experimentation. The ratio of height-to-width (10:65) and width-to-depth (10:90) places an open head joint brick vent in a relatively unexplored area of orifice flow. Brick vents cannot be assumed to behave as a simple infinitely wide slot (i.e., ignoring the effect of the two short sides). They are too deep to behave as a square-edged orifice and too shallow to act as a pipe. In practice, vent inserts are often used to resist direct rain penetration and to keep insects out; it was thought that these inserts might affect the air flow characteristics. The performance of four types of commercially available vent inserts has therefore also been evaluated.

- **Large slotted openings.** Open joints, for whatever reason, in natural stone cladding, precast panels, and other panel cladding systems are common. Many European drained and back-ventilated systems utilize a series of horizontal openings at the panel joints. Depending on the nature of the screen, the width ranges from about 5 mm to 20 mm and the depth (thickness of the screen) from about 10 to 100 mm.

Semi-continuous slots (i.e., slots with a length many times their height or width) are sometimes used for venting cavities in the building envelope. Slots of this nature, because of the large venting area, provide comparatively little resistance to airflow. The width-to-height aspect ratio of a brick vent (approximately 1:7) represents one extreme of expected deep slot behaviour. A higher aspect ratio (1:15) and shallower (i.e., thinner cladding) slot will provide less resistance to flow; such slots can be realistically modeled as infinite-length, square-edged orifices.

Large slotted openings.



Rectangular Openings

Small Round or Oval Openings.

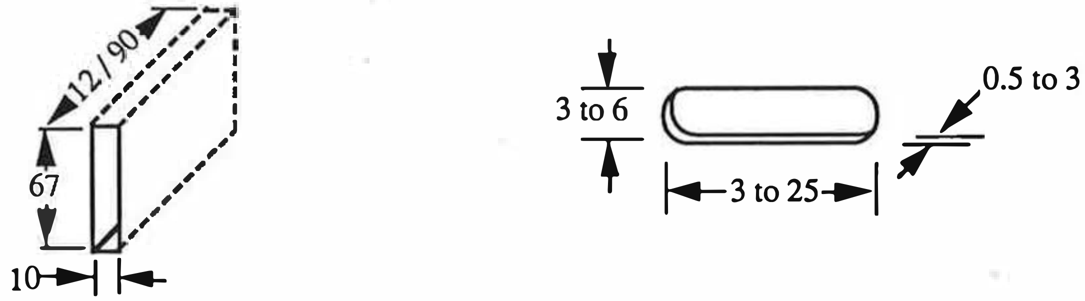


Figure 2.1: Typical Vent Geometries and Sizes

2.2 Orifice Flow: Basic Theory

The volumetric fluid flow rate through a sharp-edged orifice as a function of a pressure difference is usually described by the fundamental relationship [23]:

$$Q = C_d \cdot A \cdot \sqrt{\frac{2 \cdot \Delta P}{\rho}},$$

where Q is the volumetric flow rate,

A is the area of the orifice,

ρ is the density of the fluid,

ΔP is the pressure difference, and

C_d is a factor that accounts for friction and turbulence losses.

This relationship can be derived from Bernoulli's basic flow equation. The value of C_d (the so-called discharge coefficient) must be applied to match actual measurements and can be derived analytically only for some unique situations. The discharge coefficient comprises two parts: the contraction coefficient, C_c, and the velocity coefficient, C_v. The former coefficient accounts for the fact that the flow narrows as it flows through the orifice. The second coefficient accounts for losses due to friction and turbulence.

For turbulent (high-speed) flow through a circular sharp-edged orifice, Kirchoff calculated a discharge coefficient of $\pi/(\pi+2) = 0.611$; this is still commonly used as a datum in much of the building science literature.

Flow through deep orifices, cracks, or slots can be better described by the more general power law expression:

$$Q = C_d \cdot A \cdot \left(\frac{2 \cdot \Delta P}{\rho}\right)^n,$$

where all variables are as before but the square root has been replaced by the flow exponent, n.

For sharp orifices and large openings and turbulent flow, the equation simplifies to the same equation as before (i.e., $n = 0.5$). For laminar flow, the choice of a higher value of n (but always less than 1.0) provides a better fit to the data and is theoretically more acceptable. A flow exponent of 0.5 indicates that the flow is completely turbulent. An exponent of 1.0 indicates that the flow is completely laminar.

Although the power law form is widely used to relate the pressure drop and the flow rate through building envelope assemblies and components, it should be noted that there is an increasing volume of research that questions the validity of this law [24 - 28], especially at low flows and for small opening sizes. ASHRAE [29] suggests that the power law can be used to describe flow through normal orifices for Reynolds numbers as low as 250 (the Reynolds number, discussed later in this report, is a non-dimensional number which relates inertial to viscous forces in fluid flow). Nevertheless, until more compelling experimental results prove otherwise, the power law is likely appropriate and presumably sufficiently accurate for the vent openings of interest and the flow rates that occur in wall vents.

Orifices that are very carefully calibrated for use as international (ISO) or industry (ASTM) standards generally have higher discharge coefficients than that derived by Kirchoff, and, more importantly, the discharge coefficients vary with the speed of the flow (more precisely, with the Reynolds number). These standards also tend to restrict the minimum orifice size to 12 mm. Figure 2.2 presents the C_d values (equal to $C_c \cdot C_v$) for such a standard orifice and a standard nozzle. At very high flows, the discharge coefficient may indeed converge to a value of 0.61, but flows this high are rarely approached in building envelopes. The standards rigidly define the location at which the pressure is measured in order to ensure repeatable results. However, the choice of pressure tap size and location is based on practical application and not theoretical considerations; therefore, measured discharge coefficients rarely match theoretically derived values [30].

2.3 Static Pressure Vent Tests

The measurement of the flow characteristics of the various vent types over a range of steady-state flow rates was used as a starting point for the experimental program. Note, however, that ventilation flow are likely to be very slow and somewhat variable, and pressure moderation flows are likely to be highly variable about a mean that is often close to zero. Matching results from steady-state flow to more realistic conditions has been attempted so that existing research can be used to validate and extend our results.

2.3.1 Objective

The objective of the static vent flow experiments was to characterize a vent in terms of the discharge coefficient, C_d, and the flow exponent, n. These values can then be compared to other research as well as providing a full description of the volume of air flow that can be expected when a vent is under a given air pressure difference.

2.3.2 Apparatus

The apparatus developed to conduct the steady-state flow experiments consisted (Figure 2.3) of a fan to produce the flow, valves to regulate the flow, and a 1.2 m long, 250 mm diameter plexiglass pipe to which one of the vents could be attached. Instrumentation included a group of

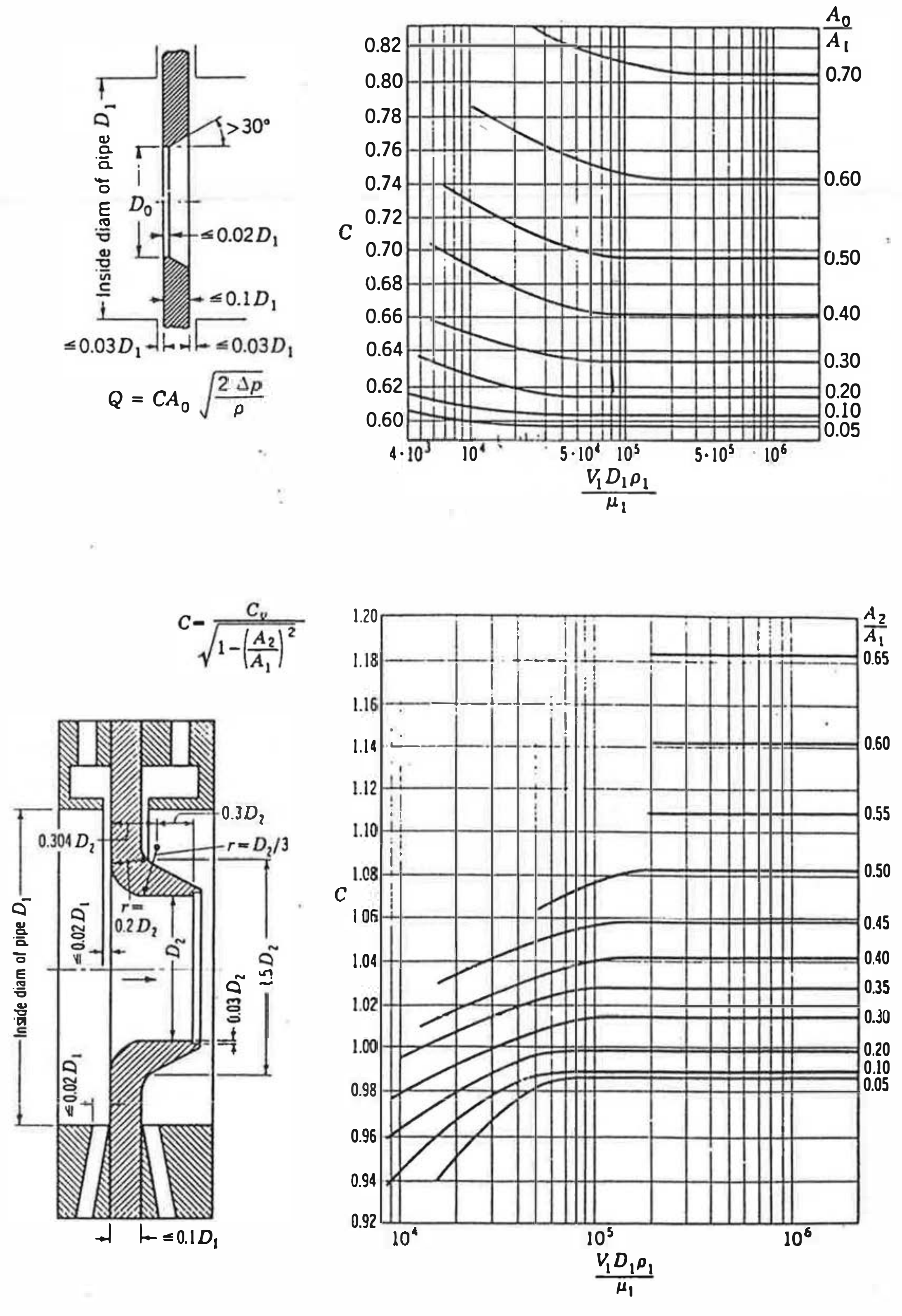


Figure 2.2: Discharge Coefficients for Industry Standard Orifices [23]

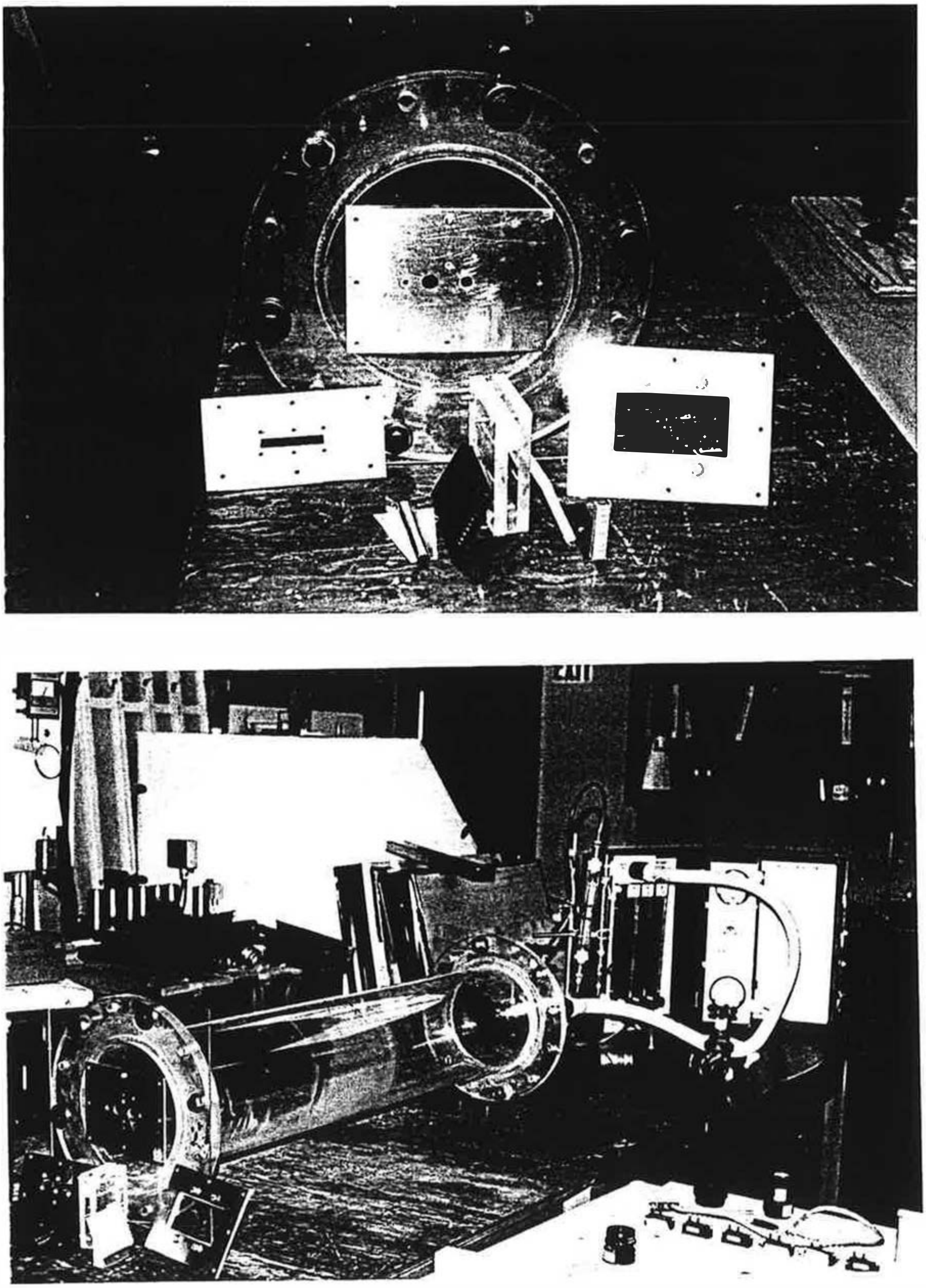


Figure 2.3: Photo of Test Set-up for Examination of Steady-Flow Vent Characteristics

parallel flowmeters that could measure flows (from 0.02 l/min to 200 l/min), and pressure transducers or gauges to accurately measure the pressure drop (from 0.1 Pa to 3000 Pa).

The plexiglass pipe served several functions. Its length ensured that flow from the fan was stabilized before reaching the vent test section. Its diameter was chosen so that the vent would be exposed to an approaching flow very similar to that in actual wall vent (i.e., the diameter of the pipe was very large in relation to the diameter of the vent). The volume of the pipe was such that it acted as a reservoir and ensured that small, short-term flow variations were damped out. The transparent pipe also permitted the nature of the flow to be observed, i.e., smoke could be added to the air flow and the nature of the flow could be clearly observed.

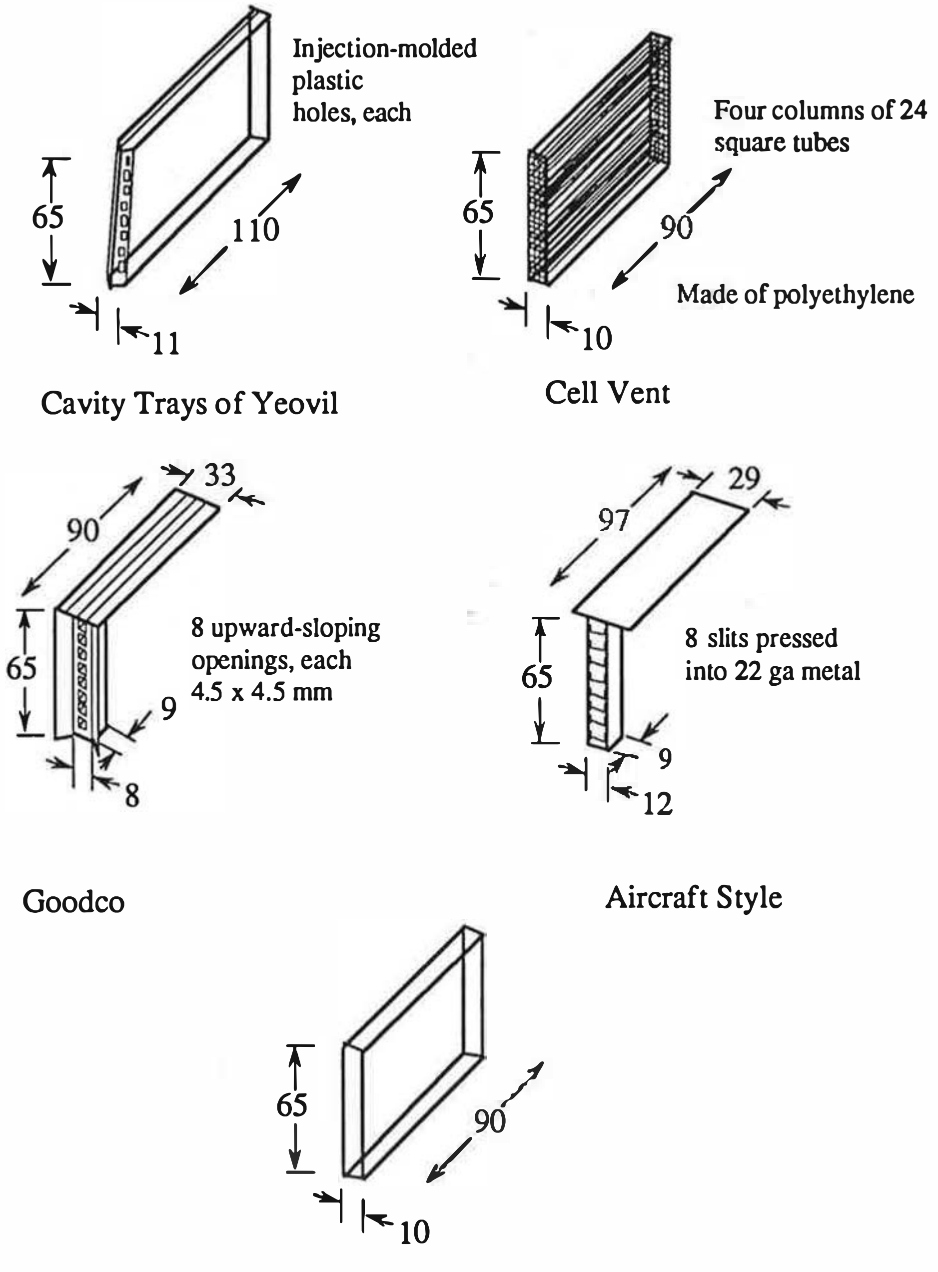
The commercial vent inserts tested are shown in Figure 2.4.

2.3.3 Procedure

Before beginning each series of steady-state tests, the vent test section was installed and the vent opening tightly sealed. The leaks in the test system (air flow through connections, seals, etc.) were then found by applying several large pressures and measuring the flow. Because the system was exceptionally tight, pressures of over 500 Pa were often needed to generate measurable leakage.

The vent was unsealed and the flow and related pressure were recorded at 15 to 30 points in roughly equal steps of increasing pressure and then in steps of decreasing pressure. Three or more similar runs were generally conducted. The temperature of the air was relatively constant during all tests.

The discharge coefficient and flow exponent were calculated from the recorded data using a least-squares regression analysis.



Cavity Trays of Yeovil

Cell Vent

Goodco

Aircraft Style

Open Head Joint

Figure 2.4: Commercial Masonry Veneer Vent Inserts Tested

2.3.4 Results

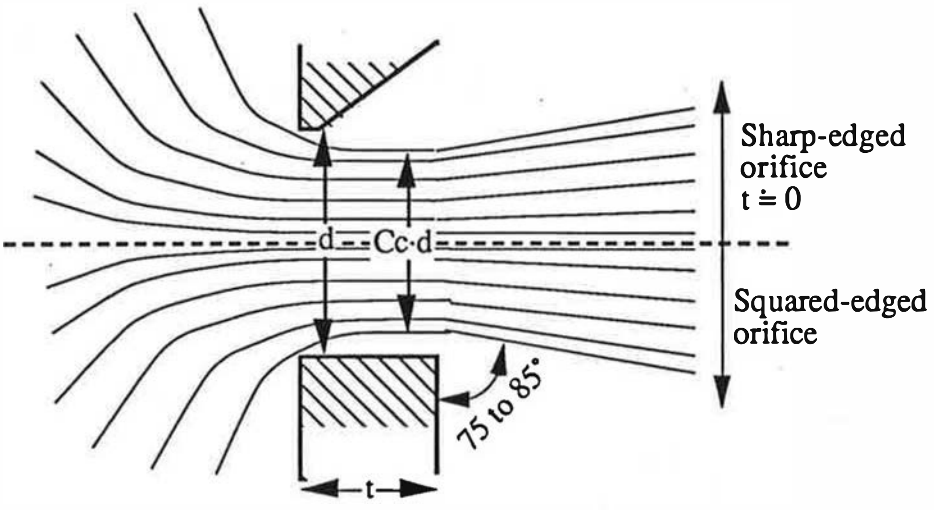
From the literature review and flow visualization experiments we conducted, an understanding of the behavioural aspects of orifice flow was developed. Figure 2.5 and the discussion below summarizes this behaviour.

Flow through sharp-edged orifices (thickness-to-diameter ratio = t:d< 0.5) was similar to theory – air was attracted from all directions on the high pressure side and the flow contracted just past the upstream edge of the entrance. The exit stream was a relatively sharply defined sharp cone with an angle of 10 to 15° degrees off the centreline, even at very low flows. This behaviour did not change over the range of pressures tested (1 to 500 Pa). The contraction coefficient, C_c, is indicated in Figure 2.4a.

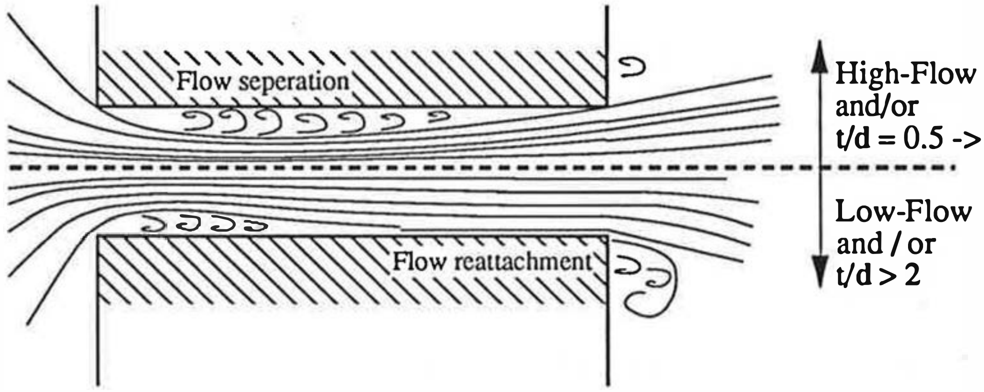
Flow through deeper orifices (larger t:d ratio), such as the open brick head joint and the 90 mm deep pipe, behaved as shown in Figure 2.4b and c. For low flows or shallow orifices the flow expanded past the entrance and, although it began to interact with the exit edge, it remained separated or detached flow. As the flow was increased, or the orifice was made deeper, the flow would reattach to the sides of the orifice before exiting. This latter behaviour was unstable, and flow could switch between attached and unattached flow at the same flow level – this change in behaviour may result in a change in the flow vs. pressure plot and generate hysteresis effects during a test.

When the orifice is many times deeper than its diameter, the flow consistently reattaches to the side of the orifice and takes on a stable velocity profile. The reattachment may occur after as little as 10 diameters from the entrance but may require as much as 100 diameters [31]. If the flow is slow enough, it behaves laminarly and a parabolic velocity distribution forms. Once the flow passes a threshold flow level and becomes turbulent, a blunter power-law profile forms. For the deep orifices typically used in buildings (i.e., a t:d ratio less than about 8), reattachment would not occur for pressure differences greater than about 0.1 Pascals.

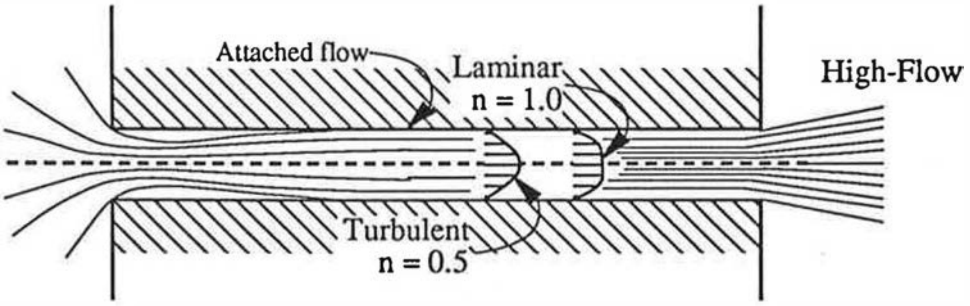
The steady-state flow test results (Table 2.1) have shown that simple orifice theory (i.e. C_d=0.61 and n= 0.5) is relatively accurate for the tested orifices with a diameter of more than 12 mm (t/d < 0.25) but that small holes (t/d > 0.5) have higher C_d values (i.e. higher flow) than would be predicted. This behaviour is predicted by theory and has been measured by other researchers. In fact, the measured discharge coefficients for the tests with t/d> 0.5 are in good agreement with some of the literature [32]. The results for the 15.8 mm Ø orifice are close to simple theory, whereas the 12 mm, 6 mm, and 3 mm have increasing values for C_d with flow exponents of almost 0.5. The 1.5 mm Ø orifice has a smaller C_d than the 6 mm orifice but the flow exponent is larger than 0.5; hence, for the very small orifices, flow at a given pressure is proportionally higher than predicted by simple orifice theory.



(i) Orifice: t/d < 0.5



(ii) Deep Orifice Flow: 10 < t/d < 0.5



(iii) Pipe Flow: t/d >> 10

$$Q = C_d \cdot A_{vent} \cdot \left(\frac{2 \cdot \Delta P}{\rho}\right)^n \qquad C_d = C_c \cdot C_v$$

Figure 2.5: Generalized Observed Steady Flow Behaviour Through Building Vents

Orifice Diameter (d) x Depth (t) [mm]	Depth (t): Diameter (d) (t:d)	Pressure Range [Pa]	Discharge Coefficient (C_d)	Flow Exponent (n)
25.4 x 3.0	0.12	5 - 250	0.652	0.503
22.65 x 3.0	0.13	5 - 250	0.643	0.503
19.0 x 90.0	4.73	5 - 250	0.673	0.498†
15.8 x 3.0	0.19	5 - 500	0.675	0.503
12.0 x 3.0	0.25	5 - 500	0.666	0.515
6.0 x 3.0	0.50	5 - 75	0.804	0.493†
3.0 x 3.0	1.00	5 - 500	0.894	0.507
3 (square-edged) x 3	1.00	5 - 500	0.868	0.510
1.5 x 3.0	2.00	5 - 500	0.789	0.537

Note: Linear regression best-fit to flow equation $Q = C_d \cdot A \cdot (\Delta P)^n$. Simple theory: $C_d = 0.611$, $n = 0.5$

† The value for n cannot, theoretically, be less than 0.5. Experimental noise is the cause of these values.

Table 2.1: Sharp-Edged Orifice Flow Coefficients from Steady-State Flow Tests

Masonry Vent Type (10 x 65 mm head joint)	Discharge Coefficient (Cd)	Flow Exponent (n)
Open	0.626	0.555
Cell-Vent	0.089	0.720
Goodco	0.047	0.515
Yeovil	0.056	0.555
Aircraft	0.030	0.497

Note: Linear regression best-fit to flow equation $Q = C_d \cdot A \cdot (\Delta P)^n$. Area based on an open head joint.

Table 2.2: Orifice Flow Coefficients from Masonry Vent Insert Tests

The flow exponent begins to diverge from 0.5 for the smallest orifice because the t:d ratio approaches 2, and thus flow behaves slightly more like laminar pipe flow (note, for laminar flow n=1.0) despite the sharp-edged bevel. The brick vent and inserts discussed below also clearly show how the flow exponent reflects whether the flow is laminar or turbulent. For diameter-to-thickness ratios of more than 2, the flow coefficient appears to stabilize at about 0.65 with a flow exponent of 0.50.

The 90 mm deep pipe behaved remarkably like an orifice since, over the pressure differences tested, it was observed that the flow did not reattach to the sides of the pipe. The flow in a smaller diameter pipe (say 3 or 6 mm diameter) might have reattached to the sides of the tube and resulted in more laminar flow (i.e. n > 0.5).

The brick vent (C_d=0.63, n=0.56), despite its rectangular aspect ratio and depth, behaved in a very similar manner to a large orifice. The discharge coefficient for the brick vent inserts was not calculated because measuring the area of the openings in the inserts is difficult. Instead, an equivalent discharge coefficient was calculated based on the full area of the vent (10 x 65 mm). This method of presentation is also more useful for comparing the venting efficiency of the different products to each other and to an open head joint.

The flow exponent calculated from the results of the open brick vent tests indicate that flow begins to diverge slightly from perfect turbulent flow, almost certainly because of the vent's depth. At very low pressure differences (much less than 1 Pa), the flow exponent can be expected to be higher because the flow will reattach to the sides of the vents.

The discharge coefficient and flow exponent of the inserts are presented in Table 2.2. Not surprisingly, the Cell-Vent (n=0.72), essentially a series of 1 mm square pipes 90 mm long, behaves in a manner much closer to laminar flow than any other configuration. The other vent inserts did not modify the nature of the flow significantly.

The results of the tests of the commercially available inserts show that all of the inserts severely restricted the flow of air. The best insert, Cell-Vent, restricted flow to less than 15% of the flow through an open head joint. The Goodco, Yeovil, and aircraft-style inserts all restricted flow to between 5 and 8% of the flow through an unobstructed vent. Compare the plots of flow versus pressure of the various brick vents in Figure 2.6. Clearly, the flow restriction of all the vent inserts may have serious negative implications for both ventilation and pressure-moderation.

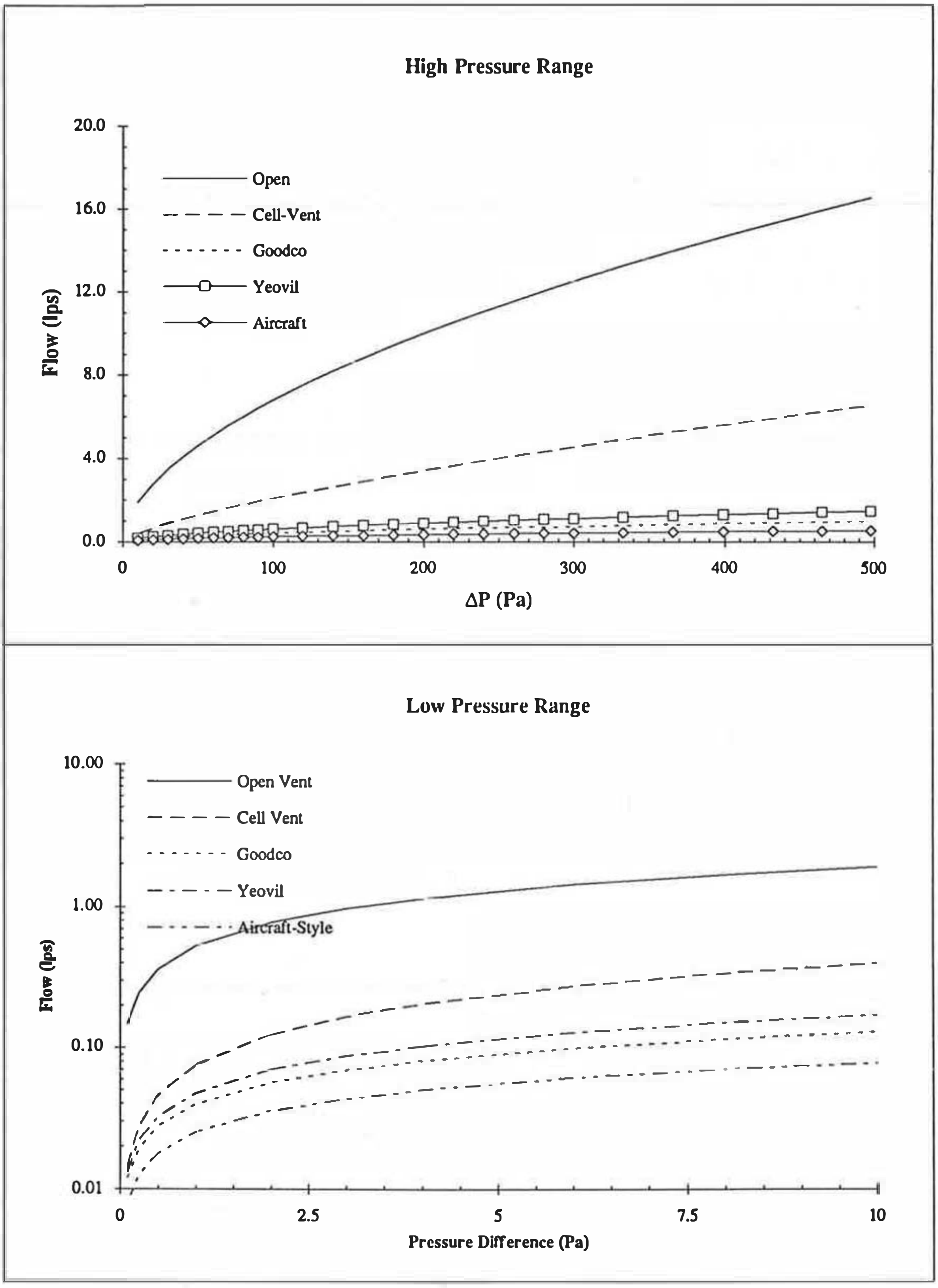


Figure 2.6: Masonry Vent Static Pressure Test Results

2.4 Dynamic Pressure Vent Tests

A series of tests was also conducted, mostly on the brick vent models, to quantify the differences in flow behaviour between static and dynamic pressure differences across orifices. Using the steady-state flow results as datum, we compared the results from the dynamic tests to predictions in an attempt to quantify the differences between dynamic and steady-state behaviour.

Dynamic pressure measurements are difficult to conduct, especially for low pressures and high frequencies. Measurements require a sensitive, accurate, and fast response electronic pressure transducer and a high-speed data acquisition system. A resolution of approximately 0.5 Pa and 1 millisecond was achieved.

2.4.1 Objectives

In an attempt to measure performance under conditions comparable to those in service, the effects on vent flow of different pressure amplitudes, frequencies, and mean flows were considered. Because the pressure drop across the vent opening varies in a non-linear fashion (i.e., linear with $\sqrt{\Delta P}$), the amplitude of the pressure variation will have an effect – as will the mean velocity of air flow through the vent hole (i.e. because of inner wythe air leakage in a wall). The behaviour of several types of brick vents were measured for three different frequency oscillations (1, 0.5, 0.2 Hz) at three different mean pressure amplitudes (0, 100, 300 Pa). Therefore, the dynamic test series contained 9 tests for each of the five brick vents. The test series is summarized in Table 2.3. Because of the flow restriction caused by most vent inserts, the higher-frequency tests (i.e., periods of 1 and 2 seconds) could not be conducted without generating pressures of more than 1250 Pa (the maximum pressure measurable with our equipment).

2.4.2 Apparatus

The dynamic vent test apparatus consists of a pipe (the same diameter as the static test apparatus), a stiff aluminum piston, and a driving mechanism that drives the piston back and forth (Figure 2.7 and 2.8). The pipe used was shorter than the one used in the static pressure tests to minimize the volume of air and thus ensure a very fast response of the air pressure to piston movements. The instrumentation consists of high-speed electronic pressure transducers (± 12.5, ±250, and ± 1 250 Pa range with a response time of about 5 ms), a direct current displacement transducer (with a response time >> 2 kHz) and a high speed (2 kHz) data acquisition system. The vent is attached to the open end of the pipe and the same fan and flowmeter system used for the static tests were used to apply a mean pressure difference. The back pressure of the flowmeter and fan was high enough to ensure that dynamic oscillations in the downstream side

Vent Type	Applied Pressure (Pa)		Period (s)	
		1	**2**	**5**
Open Vent (10 x 65 mm)	0	√	√	√
	-100	√	√	√
	-300	√	√	√
Cell Vent	0	√	√	√
	-100	√	√	√
	-300	√	√	√
Goodco Vent	0	>	>	√
	-100	>	√	√
	-300	√	√	√
Yeovil Vent	0	>	>	√
	-100	√	√	√
	-300	√	√	√
Aircraft Style	0	>	>	√
	-100	>	√	√
	-300	>	√	√
Orifice 22.6 Ø mm	100	√	√	√
	0	√	√	√
	100	√	√	√
Pipe 19 Ø x 90 mm	-100	-	√	√
	0	√	√	√
	100	√	-	√
Orifice 25.4 Ø mm	0	√	-	-

Notes: √ indicates test was conducted
> indicates test pressures exceeded ± 1250 Pascals
- test not conducted

Table 2.3: Dynamic Pressure Vent Test Series

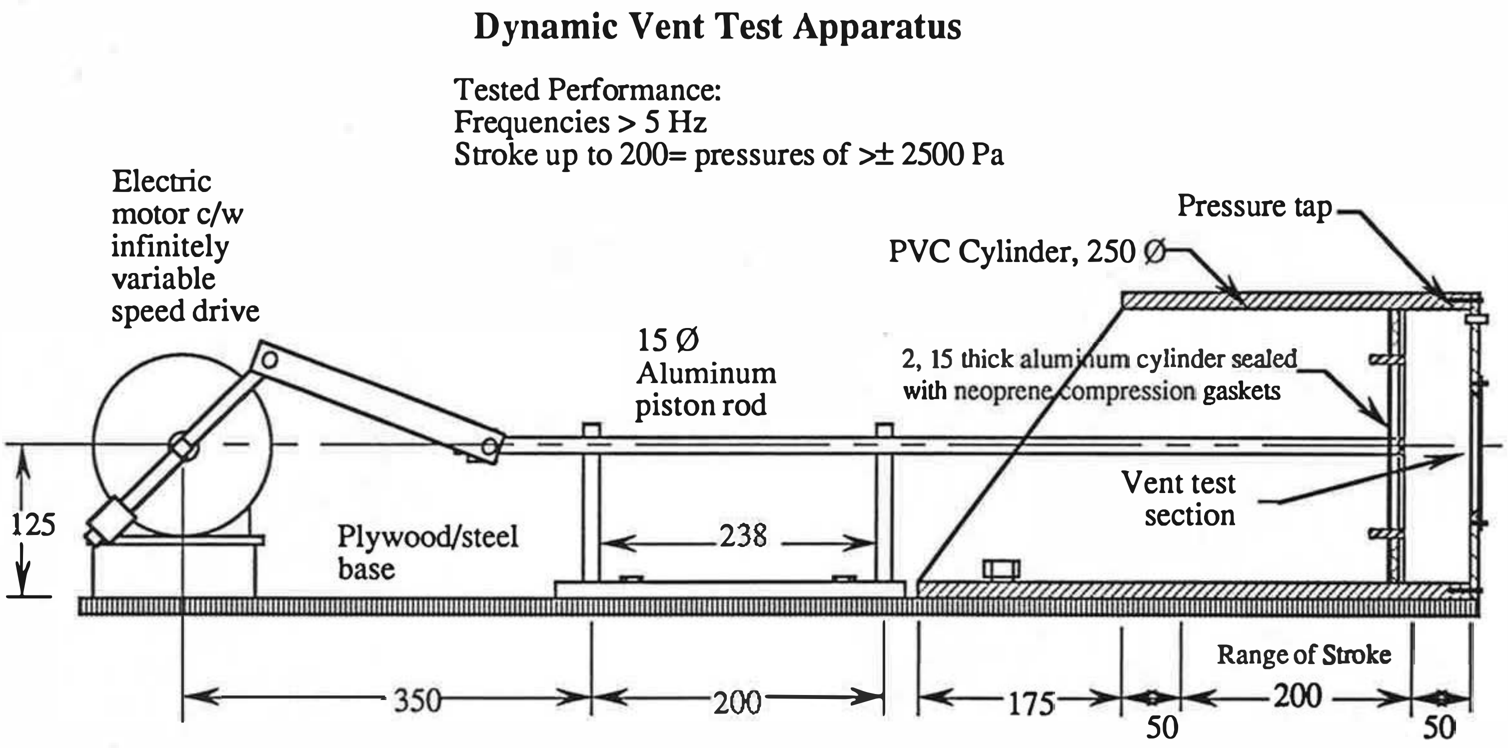


Figure 2.7: Dynamic Pressure Vent Test Apparatus

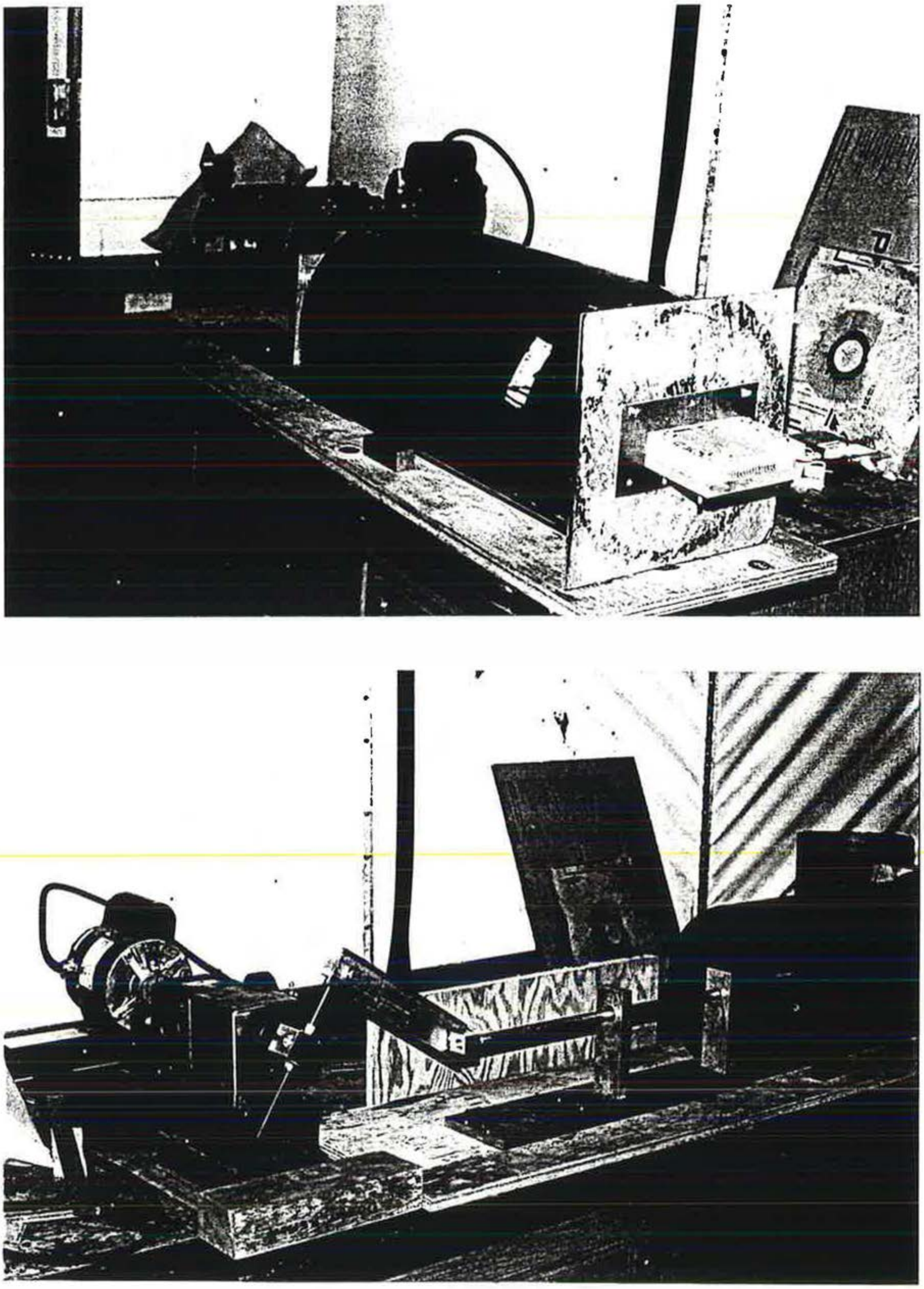


Figure 2.8: Photo of Dynamic Pressure Vent Test Apparatus

resulted in flow variations of less than 5% of the applied flow. The apparatus could provide frequencies of more than 5 Hz and pressures of up to at least 2 000 Pa.

2.4.3 Procedure

Before each dynamic test, the leakage of the system was measured and set to zero if possible. A pressure difference was applied (if applicable), the data acquisition was started and, after a pause of about 0.5 seconds, the dynamic vent test machine was started. The short pause provided an accurate record of the zero value of all transducers.

2.4.4 Results

The experimental apparatus used for the dynamic tests returned excellent and repeatable results. However, the interpretation of the results is difficult.

By comparing displacement and pressure measurements it was established that the time lag between application of the displacement and a pressure rise was very small – less than 10 ms. This conclusion matches theoretical predictions based on the compressibility of air and further suggests that Helmholtz resonator models (which predict a pressure difference across the screen due to a time lag in pressure response) are probably poor predictors of pressure moderation performance.

A computer program was written to simulate the pressure variations in the dynamic vent test apparatus. The program calculates the flow through an orifice and the pressure within the cylinder at many small time steps given the C_d and n values. The stroke and frequency were summarized from the recorded measurements. The program calculated the pressure in the chamber using the measured area of the orifice being tested. Four calculation procedures were tried, namely:

1) using the theoretical C_d and n values (i.e. $C_d = 0.611$ and $n = 0.5$)
2) using the C_d and n values from the static pressure tests, (i.e. Table 2.1 and 2.2),
3) choosing a C_d which best fit the data (especially the maxima and minima) using a flow exponent of 0.5,
4) choosing a combination of C_d and n that would best fit the data.

Table 2.4 summarizes the results of the measurements and calculations. It is clear from these results that under dynamic pressures the flow through all vents is considerably higher (and thus the pressure in the cylinder is lower) than would be predicted by using simple orifice theory and measured static flow values.

Test	1	2	3	4	5	6	7	8	9
Period (s)	1.11	2.34	5.51	1.25	2.35	5.61	1.21	2.41	6.14
Stroke (inches)	1.94	1.94	2.10	1.93	1.88	1.87	1.92	1.95	1.85
Amplitude (Pa)	130	44	11	180	95	42	320	173	73
Maximum (Pa)	125	38	11	22	-11	-51	-40	-135	-217
Minimum (Pa)	-135	-50	-12	-339	-201	-135	-680	-482	-363
Applied Pressure (Pa)	0	0	0	-91	-86	-89	-289	-291	-288
Calculated Cd for n=0.5	1.37	1.14	0.97	1.20	1.04	0.90	1.09	0.98	0.89
Cd for n=0.555	1.04	0.90	0.82	0.82	0.75	0.67	0.74	0.68	0.63

Summary of Open Brick Vent Dynamic Tests

Test	1	2	3	4	5	6	7	8	9
Period (s)	1.13	2.29	6.14	1.11	2.38	5.22	1.18	2.33	5.71
Stroke (inches)	1.96	1.93	1.90	1.97	1.94	1.91	2.09	1.94	1.93
Amplitude (Pa)	623	209	59	254	141	60	389	228	99
Maximum (Pa)	598	200	58	120	2	-51	23	-109	-219
Minimum (Pa)	-647	-217	-61	-389	-280	-172	-755	-566	-416
Applied Pressure (Pa)	0	0	0	-101	-101	-101	-310	-319	-315
Calculated Cd for n=0.5	0.14	0.15	0.14	a single value could not be found to fit the measured results					

Summary of Cell Vent Dynamic Tests

Test	1	2	3	4	5	6	7	8	9
Period (s)			5.76		2.29	5.71	1.11	2.34	5.90
Stroke (inches)			1.94		1.93	1.91	1.94	1.96	1.91
Amplitude (Pa)			611		195	71	615	273	104
Maximum (Pa)			594		34	-52	296	-65	-213
Minimum (Pa)			-627		-356	-194	-934	-611	-421
Applied Pressure (Pa)			0		-97	-94	-238	-303	-293
Calculated Cd for n=0.5			0.11	a single value could not be found to fit the measured results					

Summary of Goodco Vent Dynamic Tests

Test	1	2	3	4	5	6	7	8	9
Period (s)			5.32	1.06	2.15	5.31	1.06	2.16	5.24
Stroke (inches)			1.92	1.94	1.95	1.92	1.94	1.95	1.93
Amplitude (Pa)			303	379	128	44	491	221	86
Maximum (Pa)			290	267	28	-51	164	-60	-212
Minimum (Pa)			-315	-490	-227	-140	-818	-501	-383
Applied Pressure (Pa)			0	-100	-103	-101	-311	-313	-309
Calculated Cd for n=0.5			0.14	a single value could not be found to fit the measured results					

Summary of Trays of Yeovil Vent (10 x 65 x 90) Dynamic Tests

Test	1	2	3	4	5	6	7	8	9
Period (s)			5.53		2.22	5.62		2.21	5.47
Stroke (inches)			1.91		1.94	1.92		1.96	1.92
Amplitude (Pa)			434		141	42		171	76
Maximum (Pa)			423		30	-52		-102	-215
Minimum (Pa)			-444		-253	-136		-443	-368
Applied Pressure (Pa)			0		-103	-96		-339	-301
Calculated Cd for n=0.5			0.16	a single value could not be found to fit the measured results					

Summary of Aircraft Design Vent Dynamic Tests

Table 2.4: Dynamic Vent Test Results

2.4.5 Discussion

An important result from the series of more than 50 tests is that dynamic flow through orifices cannot be easily predicted using only the steady-state C_d and n values and the compressibility of the air. For tests without an applied pressure difference (mean flow = 0), an approximate C_d value could always be chosen to fit the data. However, for tests with an imposed mean flow, no single C_d value would fit some of the results, even approximately.

For lower frequencies, the best-fit C_d values converge slowly toward the steady-state C_d value for the open vent (see Figure 2.9). It is surprising that the C_d value at the relatively slow frequency of 0.2 Hz is still significantly higher than theory would suggest. The applied mean pressure difference affected the relationship between C_d and frequency as well.

We have discovered no strong theoretical reasons for the observed behaviour of the vent flow under dynamic pressures. There are several complex potential explanations: inertia, flow interactions with the infinite reservoir outside the vent, and perhaps a type of Richardson's annular effect (a non-parabolic flow distribution sometimes observed in oscillating pipe flow [31]). The lack of hysterisis in the results seems to rule out reservoir interaction effects, but inertia is a likely force in the large amplitude experiments conducted. It might be possible to include some of these effects in a computer simulation, although the necessary physics and mathematics are not readily available.

The only similar research work found in the literature does not shed much light on the issue. In Daily et al [33], the authors conclude that "for intense jet action, as obtained with small orifice-to-tube-diameter ratios, it appears that unsteadiness produces an internal flow structure that is no longer comparable to any steady-state condition."

It is indeed possible that a steady-flow condition (i.e., laminar or turbulent) did not form in our experiments, or that flow passed through many different forms. A plug of air might be accelerated at the start of the pressure rise and the flow would have a blunt velocity profile because the friction effects along the sides of the orifice would not have time to form. This behaviour would explain the greater-than-predicted flow rates. Further into the cycle a laminar or turbulent flow profile (see Figure 2.5) might develop, only to be destroyed when the flow slows to pass through zero (i.e., almost stationary or creeping flow). Inertia effects would play a role near the middle of the orifice, but friction would play a more important effect along the sides.

Yamaguchi [34] was able to predict the results of oscillating air flow through an orifice, but the orifice-to-tube-diameter was large, in the range of 0.5, and the oscillating flow was small compared to the mean flow. In the case of our experiments, the orifice-to-tube-diameter was less than 0.1 and the oscillating flow was several times the mean flow. Inculet [3] studied scale-models of circular sharp-edged orifices with static flow discharge coefficients of 0.65 and a flow exponent of 0.5. Although she had a considerable degree of success in matching results to theory (by including the effects of inertia), the measurements taken with an imposed mean flow required a judicious "guess" of Cd to match theory, and several other factors needed to be chosen.

It should be borne in mind that, in service, dynamic pressure differences across vents are much smaller than applied in these experiments and inertia should therefore play a relatively smaller role. Future research should consider smaller pressure fluctuations (say 10 Pa) which are likely to occur more often in the field and frequencies less than 0.2 Hz since, even at this slow rate of variation, the orifices did not behave as expected.

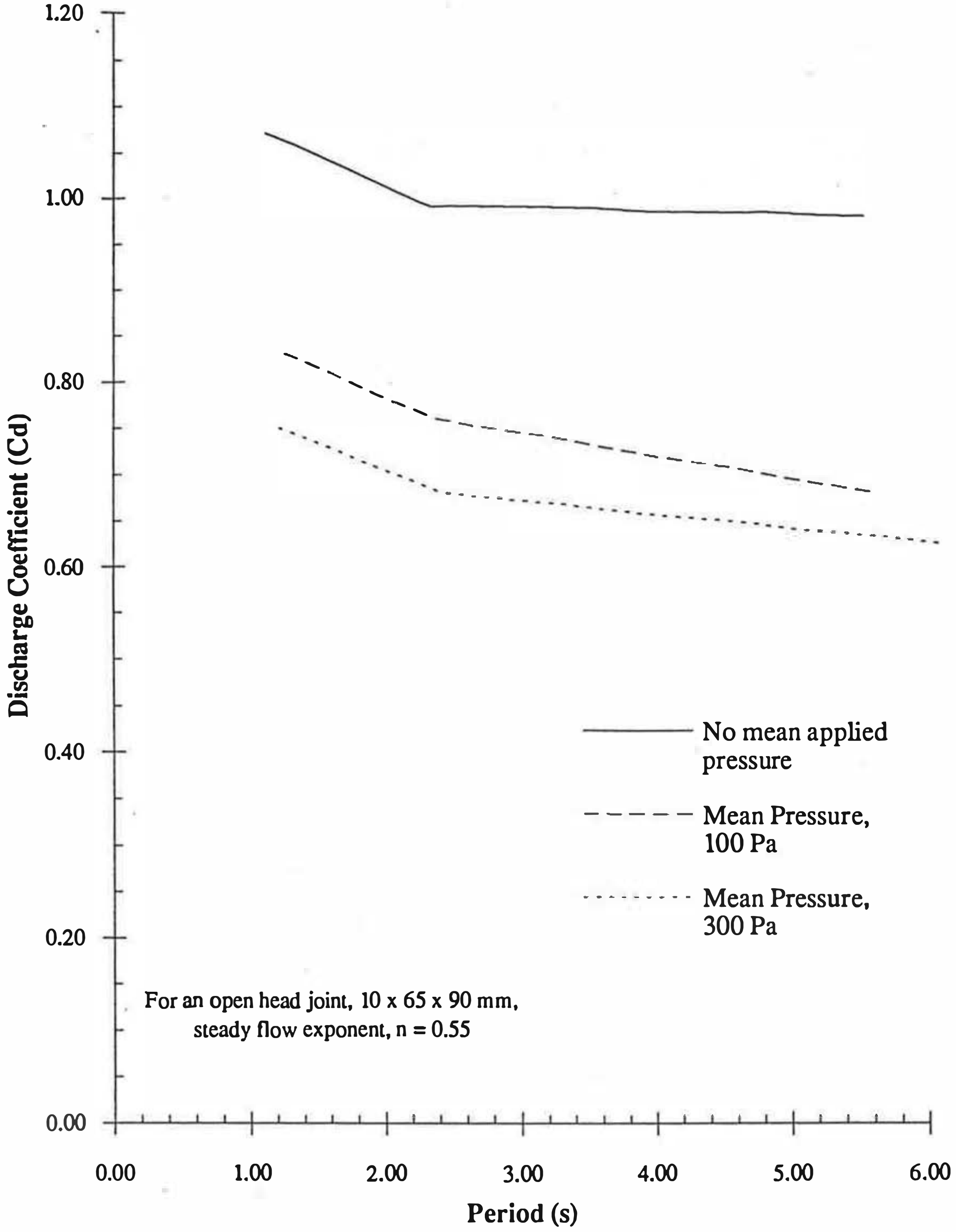


Figure 2.9: Dynamic Vent Discharge Coefficients as a Function of Frequency

3. Ventilation Driving Forces

In this chapter the primary forces that drive the mass flow of air through a cavity are identified and described. The intention is to document, quantify, and discuss the relative significance of these forces and the variables affecting ventilation driving forces.

There are two primary forces driving ventilation: thermally induced buoyancy (stack effect) and wind pressures. Secondary forces may be air movement through the wall, thermal and wind pumping, and moisture-induced buoyancy effects

3.1 Thermal Effects

Solar radiation can cause screen temperatures of more than 40 °C above ambient under some conditions. Heat energy is transferred to the air in the cavity, reducing its density. As the sun sets or passes by the face of the wall, the screen will lose its heat to the exterior until the next day when the cycle begins again. The effect of temperature on air density can generate small but significant ventilation pressures.

3.1.1 Thermal Buoyancy (Stack Effect)

The difference in density between exterior and cavity air results in buoyancy and a pressure difference. This buoyancy phenomenon is often described as the stack effect.

The density of dry air varies with temperature approximately as:

$$\rho_a = \frac{351.99}{T_a} + \frac{344.84}{T_a^2}$$

where T is the temperature in degrees Kelvin and ρ_a is the density in kg/m^3

The greater the height of the column of air in the cavity, the greater the potential difference in pressure. In Pascals, the pressure difference generated by a temperature difference (see Figure 3.1) between cavity and outdoor air is [29]:

$$\Delta P = \left[\left(\frac{352.0}{T_c} + \frac{344.8}{T_c^2}\right) - \left(\frac{352.0}{T_o} + \frac{344.8}{T_o^2}\right)\right] \cdot h \cdot 9.81$$

or more approximately, at standard temperature and pressure,

$$\Delta P = 3465 \cdot \Delta h \cdot \left(\frac{1}{T_o} - \frac{1}{T_c}\right)$$

where T is in Kelvin, pressure is in Pascals, and h, the vertical distance between vent openings, is in m.

In Figure 3.2, the resulting pressure due to thermal buoyancy is plotted against the temperature difference across the screen and vertical height between vents (at an assumed exterior temperature of 15°C; the assumed exterior temperature has little effect on the result).

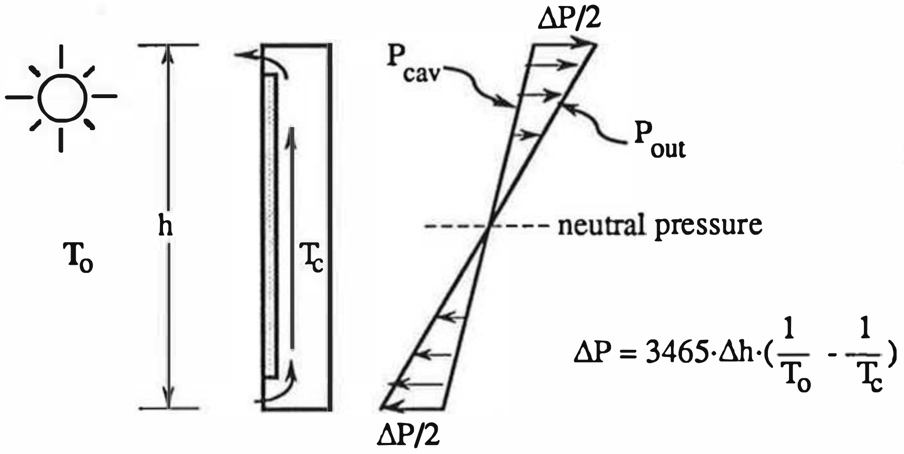


Figure 3.1: Thermal Buoyancy

Table 3.1 gives some idea of the pressures that might be generated by temperature differences. In general the cavity will be warmer than the exterior air. However, for lightweight cladding, night-time black sky radiation can cause the cladding temperature to drop as much as 3-5°C below ambient. For most cladding types, a temperature difference of 10°C will occur for a significant proportion of the time, 30°C will occasionally occur, and a difference of at least 3°C will occur for most of the time.

For a temperature difference between the exterior air and the cavity of 10°C, the pressure difference between the top and bottom of the cavity due to buoyancy over a typical 2.4 m high cavity is about 1 Pa. For tall cavities, the pressure will be proportionately higher. However, if sufficient venting is provided, the temperature in the cavity will drop as heat energy is removed by the ventilation air. In warm climates this behaviour can be used to advantage to reduce air-conditioning loads.

For 0°C outdoor temp	*Temperature Difference (Cavity - Exterior)*		
Cavity Height (m)	±3 °C ΔP (Pa)	10 °C ΔP (Pa)	30 °C ΔP (Pa)
2.4	0.33	1.08	3.02
3.0	0.41	1.34	3.77
3.6	0.49	1.61	4.53
4.8	0.66	2.15	6.03
6.0	0.83	2.69	7.54

Table 3.1 :Calculated Ventilation Pressures Due to Buoyancy

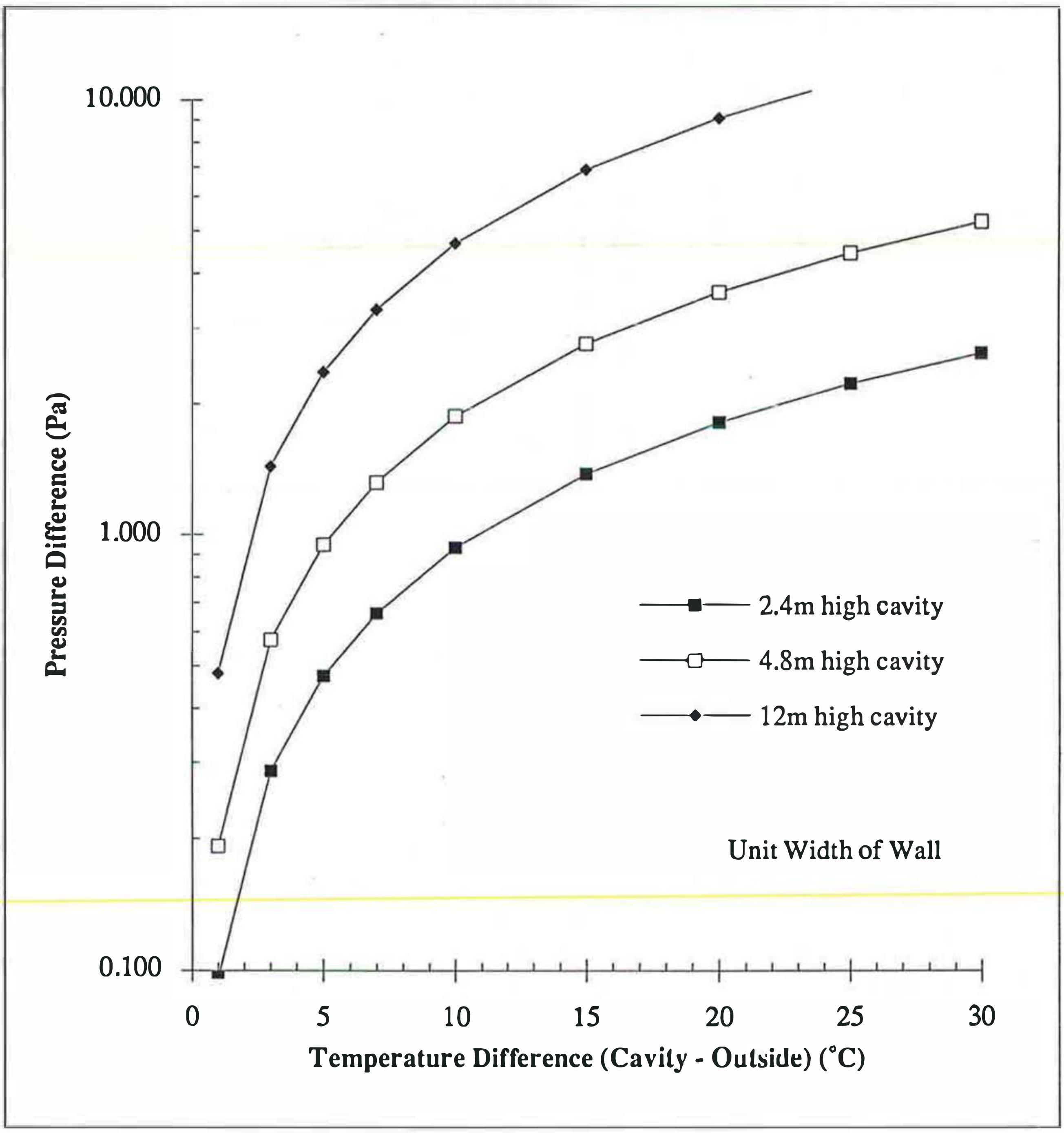


Figure 3.2: Ventilation Pressure Versus Temperature Difference and Cavity Height

Figure 3.3 plots the temperature recorded during field monitoring by BEG in a typical, west-facing brick masonry veneer wall with a 30 mm deep and 2.4 m high cavity. The temperature of the wall cavity is predominately influenced by solar radiation, and is more than 10°C above the exterior for several hours per day. On average, the cavity air in the cavity was 6°C above ambient for the entire summer, indicating an average ventilation pressure of 0.75 Pa for a period of several months. Even for the two coldest winter months, the wall cavity was 5°C above ambient.

Orientation and exposure will have a significant affect on how often and for how long thermal buoyancy pressures act, and hence how significant they are. North-facing walls will, on average, have much small temperature differences across the screen. The nature of the screen, especially its thermal conductivity, colour, and thermal storage mass, will also affect the value of the peak and mean temperatures.

3.1.2 Thermal Pumping

The daily cycle of heating and cooling of the air in the cavity will generate one diurnal cycle of expansion and contraction of the cavity air volume. As the air in the cavity expands, it is forced out through the vents or any other openings (including small pores and cracks in the cladding). Using the equation for air density as a function of temperature, the volume of air movement through the cavity due to expansion and contraction can be calculated. Over the typical range of air temperatures encountered in buildings, the change in air density is almost linear and, just as for thermal buoyancy, a simplified equation can be found:

$$\Delta V = \frac{3.546 \cdot \Delta T \cdot V}{1000}$$

where ΔV is the change in cavity volume, V, due to the rise (or fall) of the cavity temperature of ΔT (in Kelvin).

Note that the influence of this venting mechanism, sometimes called thermal pumping, is independent of the cavity volume, and venting area, etc. In all practical cases the mass exchange of air due to thermal pumping is volumetrically *very* small. For example, for a meter width of 2.5 m high, 25 mm deep cavity, a 30 °C temperature rise will result in the expulsion of:

$$3.546 \cdot 30 \cdot (2.5 * 0.025) \div 1000 = 0.00665 \text{ m3} = 6.65 \text{ liters.}$$

Since this occurs only once per day, the equivalent ventilation rate is 0.000077 liters per second!

Although thermal pumping results in the movement of a very small volume of air, it occurs in all walls, regardless of the size of the intentional vent areas. For walls with no vents, an air exchange will still take place unless the cladding is perfectly airtight (not the case in practice) or is very flexible.

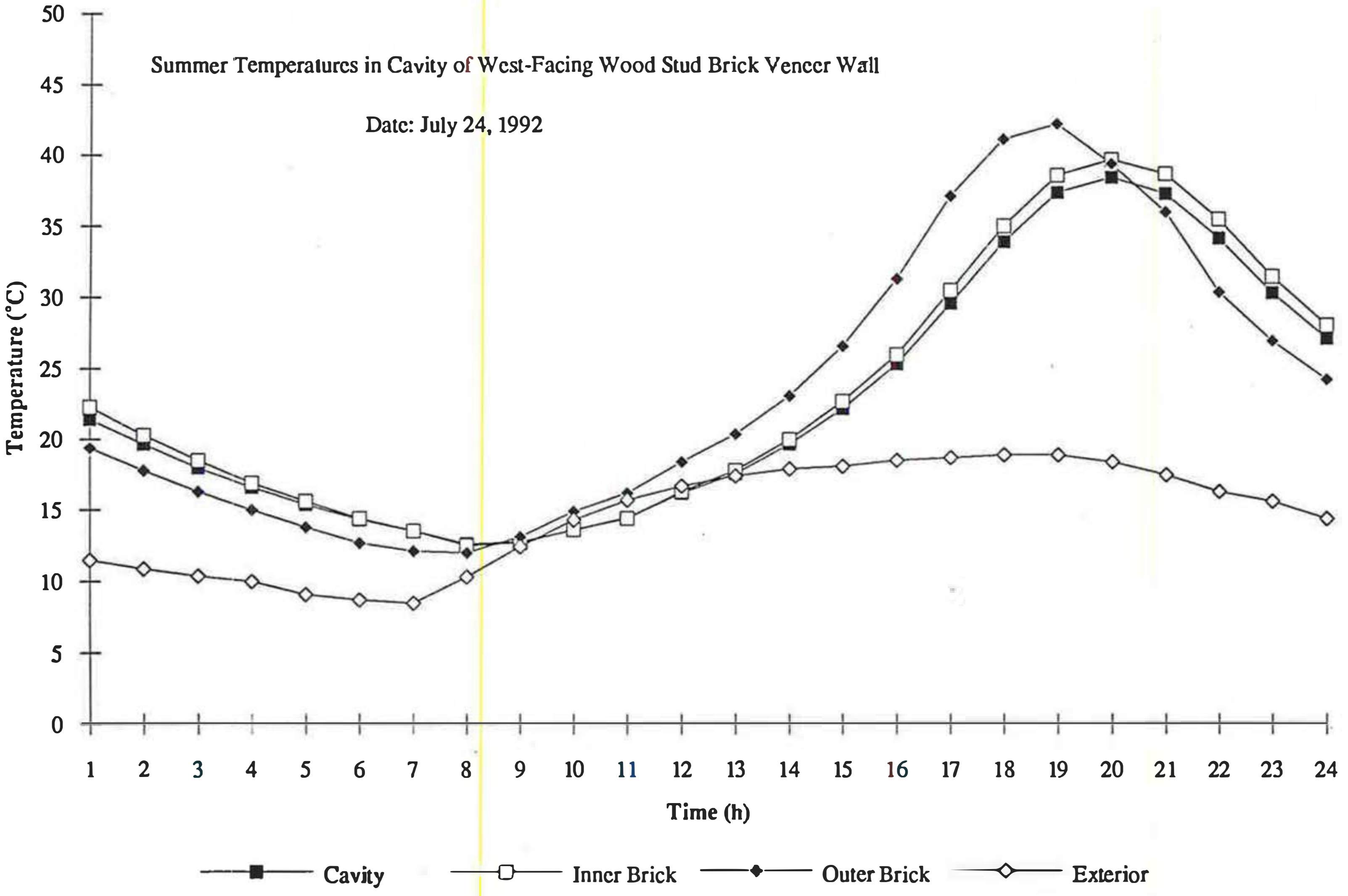


Figure 3.3: Representative Temperatures Across the Screen of a Brick Veneer Wall

3.2 Wind Effects

Wind pressures are often more significant for ventilation than thermally induced pressures; this has been confirmed by most of the research reviewed in Section 1.8. When the wind blows, gradients of pressure form over all of the surfaces of a building. These gradients are due to the vertical gradient of wind velocity (i.e., wind speed increases with height) and the horizontal and vertical gradients which form as wind flows around a structure (Figure 3.4). In relative terms, vertical gradients will be greater on short squat buildings and horizontal gradients will be larger on tall, slender buildings.

Vents that are separated by even a small distance will be exposed to different pressures because of these gradients in pressure. The pressure difference between the two vent locations may well drive ventilation air flow (Figure 3.5). Ventilation can occur through two vents separated either horizontally or vertically.

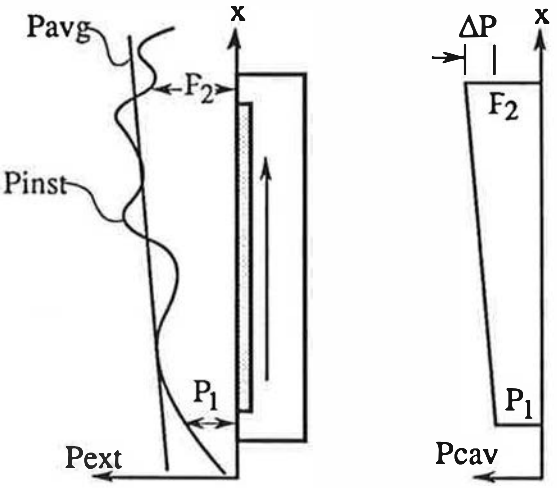
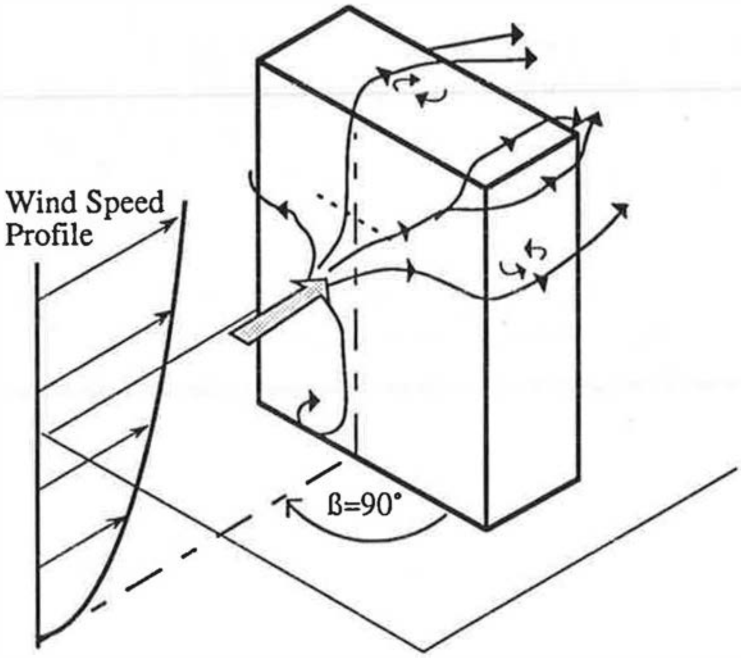


Figure 3.5: Wind-induced Ventilation Pressures

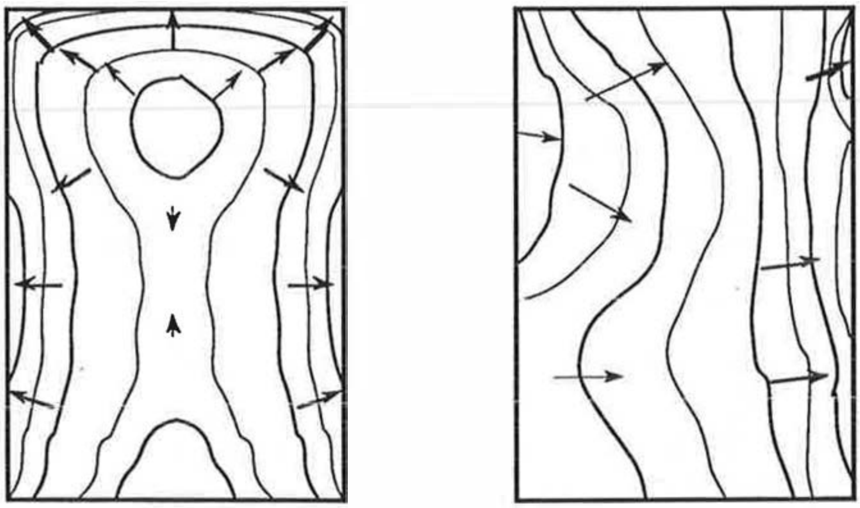
As shown in Figure 3.5, there is a relatively constant average gradient and an almost random, instantaneous short-term gradient. Because of these spatial gradients, a pressure moderated screened wall system should ideally have a compartmented cavity. If more than one vent is provided per compartment in such a system, the potential exists for significant flows of air through the compartment; although the NRCC suggests that a single vent is ideal, this is not necessarily the case (see Section 1.6).

Assuming standard temperature and pressure conditions from the NBCC, the stagnation pressure of wind can be calculated as:

$$P_{stagnation} = 0.647 \cdot v^2$$



Wind Streamlines On A Building Face



Perpendicular Wind: ß=90° Quartering Wind: ß=135°

Mean Windward Face Pressure Distributions & Secondary Flows

Figure 3.4: Wind, Air Flow , and Pressure Gradients on a Building

where the wind velocity, v, is in m/s, and

the stagnation wind pressure, $P_{stagnation}$, is in Pascals.

Wind speed, and hence pressure, varies with height. Meteorological tables generally report the wind speed at a height of 10 m above grade. An estimate of the average wind speed at z meters above grade can be found using the Simple Method of the Supplement to the National Building Code:

$$V_z = \left(\frac{z}{10}\right)^{0.1} \cdot V_{10}$$

where, V_z is the velocity a z metres above grade, and V_{10} is the velocity at 10 metres above grade.

The equivalent static wind-induced pressure on a building face is often expressed as a fraction of some reference pressure, usually either the stagnation pressure at the top of the building (eaves height for buildings with pitched roofs) or 10 m above the ground. This fraction (or pressure coefficient) can be plotted over the surface of a building for different wind conditions. The pressure coefficient, C_p, is defined as:

$$C_p = \frac{P}{P_{stagnation}}$$

The mean pressure gradients on many different buildings have been studied extensively. The expected mean pressure coefficients for several different building types are shown in Figures 3.6 - 3.8. (Note, in this context, mean is an "appropriately long time", usually 15 minutes to one hour). Within reason, the lines of equal pressure in these figures can be scaled to match the size of the building. This scaling implies that the larger the building, the smaller the pressure variation over a fixed floor height. Therefore, the ventilating pressures over a floor height on an exposed three-storey building are expected to be much more than in a thirty-storey building with the same aspect ratio.

A typical, rectangular apartment building will have a pressure coefficient that has a value of 0.7 or 0.8 near the centre and drops quickly to 0 or less near the edges when exposed to a wind acting perpendicular to the face. If the wind acts at 45° to the face, the maximum mean pressures might be slightly lower and will reduce to zero or less at the edges. Walls parallel to the wind flow will generally experience negative pressures (which can be just as effective for ventilation as positive pressures) with significant gradients. Pressures on the leeward faces will be negative and more uniform than on the other faces. A recent CMHC-sponsored wind-tunnel study [35, 36] of mean pressure gradients on the face of large apartment building models by the Boundary Layer Wind Tunnel Laboratory at the University of Western Ontario provides some very useful information regarding the potential size of ventilation pressures.

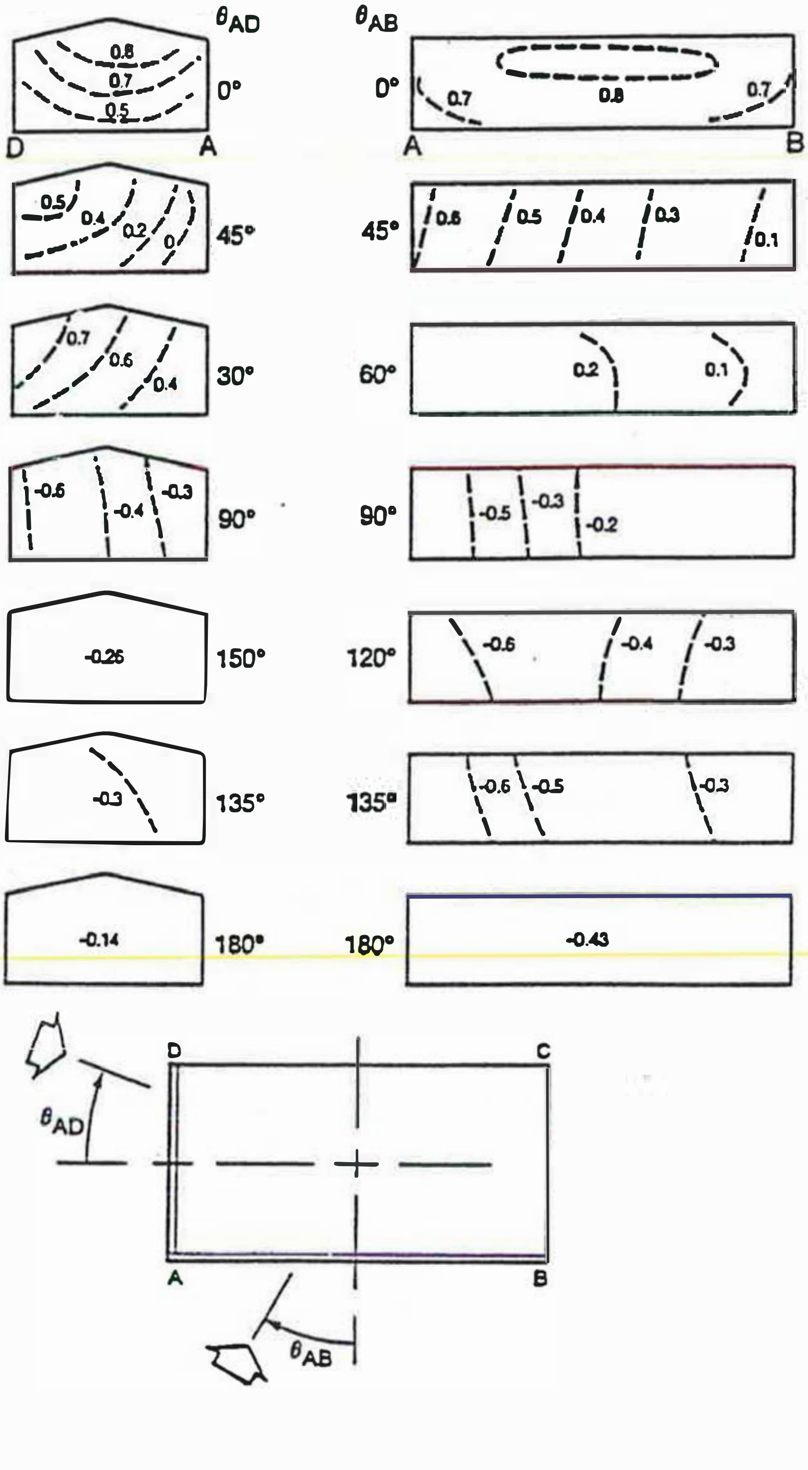


Figure 3.6:Mean Pressure Gradients on a Low-rise Building [37]

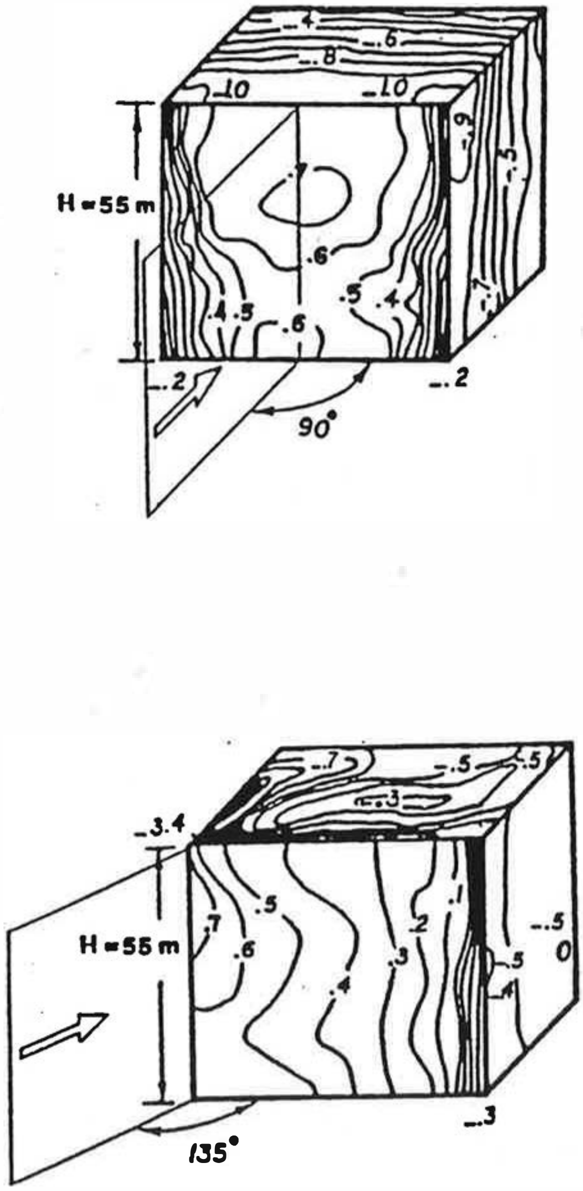


Figure 3.7: Mean Pressure Gradients on a Mid-rise Building [38]

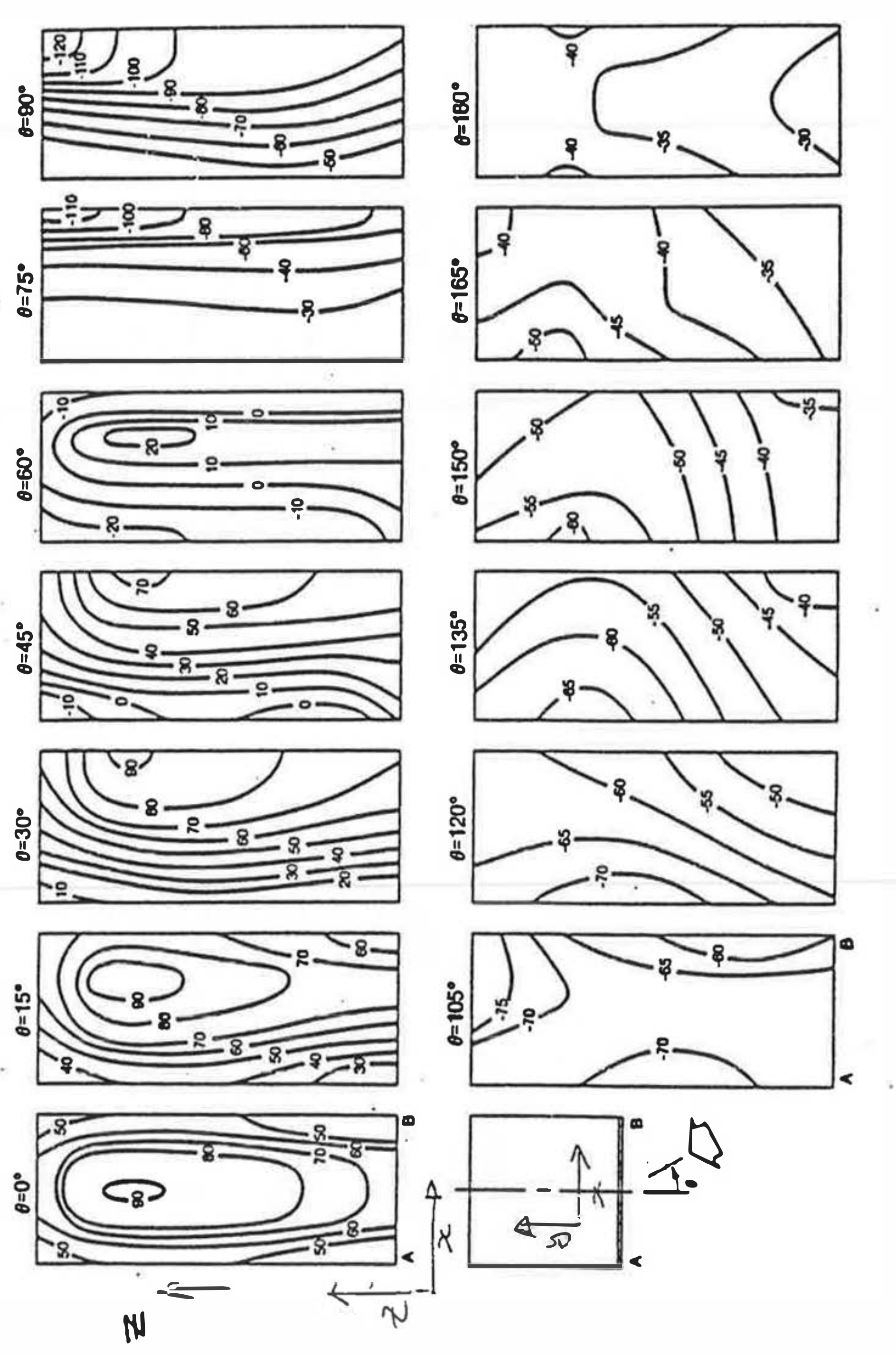


Figure 3.8: Mean Pressure Gradients on a High-rise Building [39]

The difference in pressure across two vents can also be described in a general way by the coefficient $C_{p,v}$,where the subscript v refers to venting.

$$C_{p,v} = \frac{\Delta P_{ventilation}}{P_{stagnation}}$$

where $\Delta P_{ventilation}$ is the pressure difference available to drive ventilation .

Using pressure coefficients allows data collected at one windspeed to apply to different windspeed conditions. Wind data, such as that published by the Atmospheric Environment Service [40] provide the mean hourly wind velocity as a function of direction and time of year. For many locations in Canada, the hourly average wind speed can be expected to be between 10 to 25 kilometers per hour. This translates to stagnation pressures ranging from 5 to 30 Pascals at 10 m above grade.

Appendix C contains summarized data for Waterloo, Ontario from the Atmospheric Environment Service. Given approximate ventilation pressure coefficients, data similar to this, available for all of Canada from AES, can be used to predict ventilation driving forces.

3.2.1 Field Monitoring

To calculate actual ventilation pressure coefficients, field measurements of the wind and wind pressures on a real building were undertaken.

The major variables affecting the ventilation pressures acting on a building are:

1) the size and aspect ratio of the building,
2) the windspeed
3) wind direction, and
4) the location of the vents, on the building and relative to one another

The field monitoring program devised would quantify the last three variables. Measuring ventilation pressures in the field has been very difficult in the past because such pressures are small and variable. Advances in pressure measuring technology have removed some of these difficulties.

The monitoring was conducted on the west wall of the Beghut Test Facility over the period of November to December, 1994. The Beghut is a full-scale natural exposure and test facility on the University of Waterloo campus. Figure 3.9 presents a summary of the five venting configurations (labeled 1 to 5) comprehensively measured, the dimensions of the test house, and locations of the pressure taps (labeled A to F).

The wind speed, wind direction, absolute stagnation pressure at point A, and the pressure difference between point A and the point of interest (pressure taps B to F) was measured every second. Every 15 minutes the average and standard deviation was calculated, the record was classified according to wind speed and wind direction as shown in Table 3.2, and the results saved to disk. Each of the five venting configurations shown in Figure 3.9 was monitored for a minimum of one week. Over approximately six weeks, some 3500 records were collected.

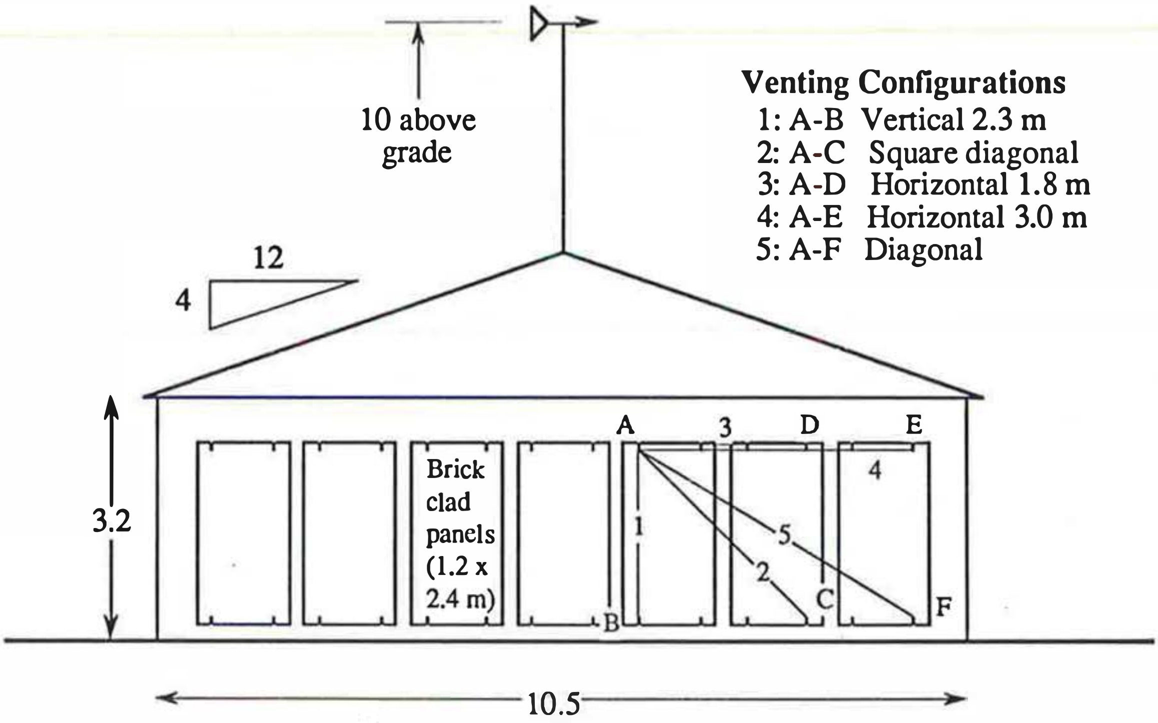


Figure 3.9: Set-up for Field Monitoring of Ventilation Pressures

A presentation of all the results and a full analysis of the collected information is beyond the scope of this report. However, some results are presented below which leads to some important conclusions for ventilation.

An example record from the field monitoring is presented in Figure 3.10. These pressures were recorded for vent configuration # 1 with the wind coming from 30° south of due west at an average velocity of 4.0 m/s (close to the annual average wind speed) at 10m. The following characteristics, which apply to many of the records, should be noted:

- as is widely known, the wind speed, wind direction and wind pressures all exhibit large, short-term variations about the mean value,
- the wind speed results in relatively small stagnation pressures at points A and B (normally between 0 and 12 Pa),
- the pressures at points A and B are different (there is a pressure gradient between A and B), and this pressure is available to drive ventilation.

For this particular wind direction and venting configuration

- the difference in pressure between points A and B, the pressure which is available to drive ventilation, is for this particular record, about 1/5 of the total pressure at A. For the purposes of ventilation, this is a relatively large force.
- the pressures at A and B are relatively well correlated; as the pressure at A rises, so does the pressure at B and thus the ratio of the ventilation pressure (A-B) to total pressure (A) is also relatively constant.

Although the stagnation pressures at A and the ventilation pressures vary between all of the records, the values could be non-dimensionalized by calculating ventilation pressure coefficients, i.e. the ratio of the ventilation pressure A-B to the calculated stagnation pressure of the wind. These ventilation pressure coefficients for each record were calculated using the average stagnation pressure at the eaves height of the Beghut (3.2 m above grade), the typical reference location for a low-rise building with a pitched roof, and the average measured ventilation pressure:

$$C_{p,v} = \frac{\Delta P_{ventilation}}{P_{stagnation}}$$

where $P_{stagnation}$ is the average stagnation pressure at the eaves height of the Beghut, and

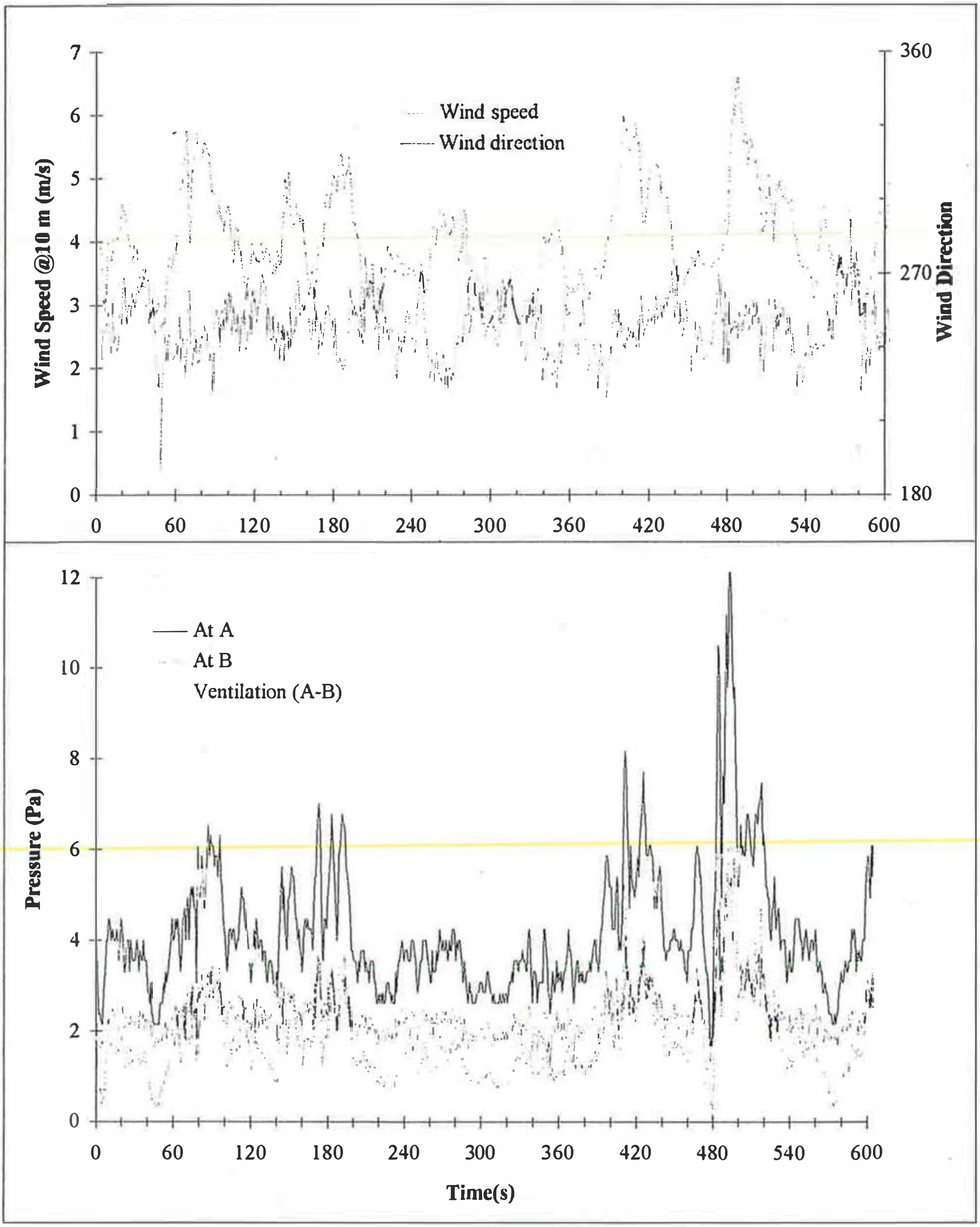
$\Delta P_{ventilation}$ is the average measured ventilation pressure.

The influence of vent configuration and wind direction can be examined using the average calculated ventilation coefficients for the many records collected during the field monitoring.

3.2.2 Mean Spatial Gradients

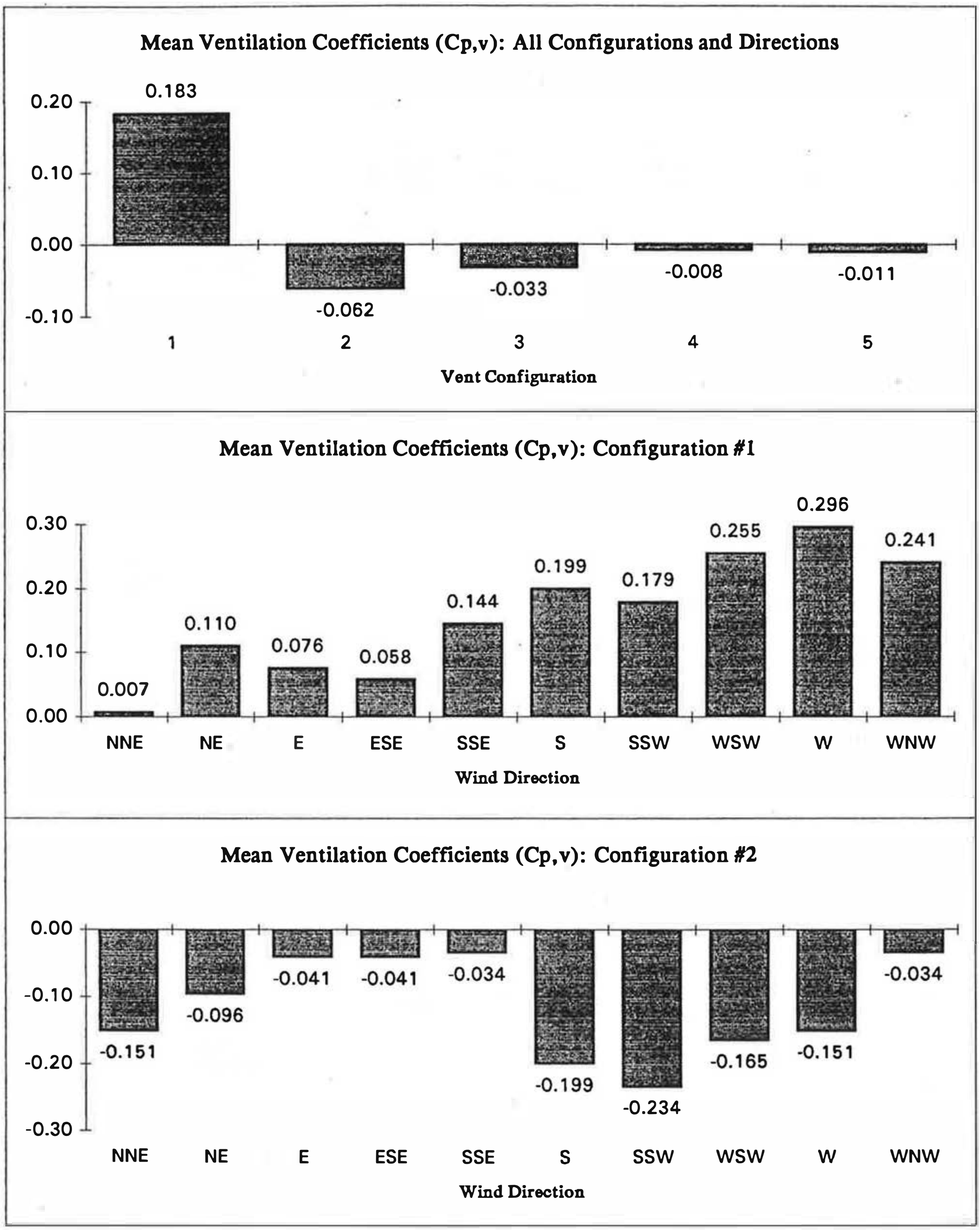
The wind pressure gradients on the face of a building vary in space and time. Only the mean spatial pressure gradients (P_{avg} in Figure 3.5) across the building face are discussed below, although the short-duration dynamic gradients (P_{inst} in Figure 3.5), called spatio-temporal in the literature, may also be important for ventilation and are dealt with in Section 3.2.3.

Figure 3.11 summarizes the mean values of the ventilation pressure coefficient from the field monitoring of each of the configurations shown in Figure 3.9 for all wind directions and speeds and for each wind direction. The value for the mean ventilation coefficient is based on from 10 to 150 records for that wind direction. The mean ventilation coefficient (based on from 421 to 1047 records) for all wind directions for each venting configuration is shown in the first bar graph of Figure 3.11. The remaining five plots present the average ventilation coefficients for



Note: Wind from West South West. Venting configuration #1. Avg. windspeed 4.0 m/s.

Figure 3.10: Example Ventilation Pressure, Stagnation Pressure, and Wind Speed Record



Mean Ventilation Coefficients (Cp,v): All Configurations and Directions

Mean Ventilation Coefficients (Cp,v): Configuration #1

Mean Ventilation Coefficients (Cp,v): Configuration #2

Figure 3.11a: Mean Ventilation Coefficients (Avg., Configurations #1 and #2)

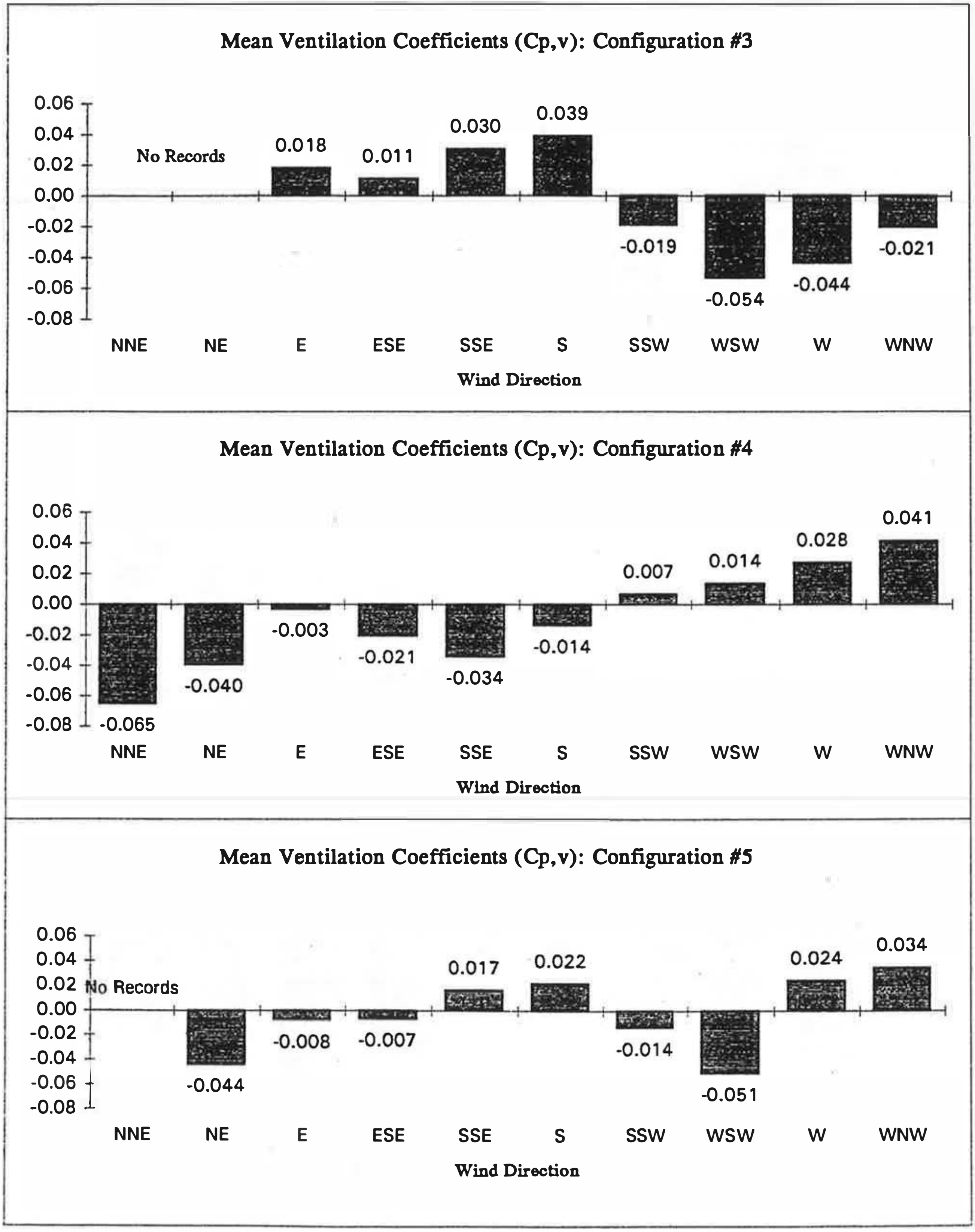


Figure 3.11b: Mean Ventilation Coefficients (Configurations #3, #4 and #5)

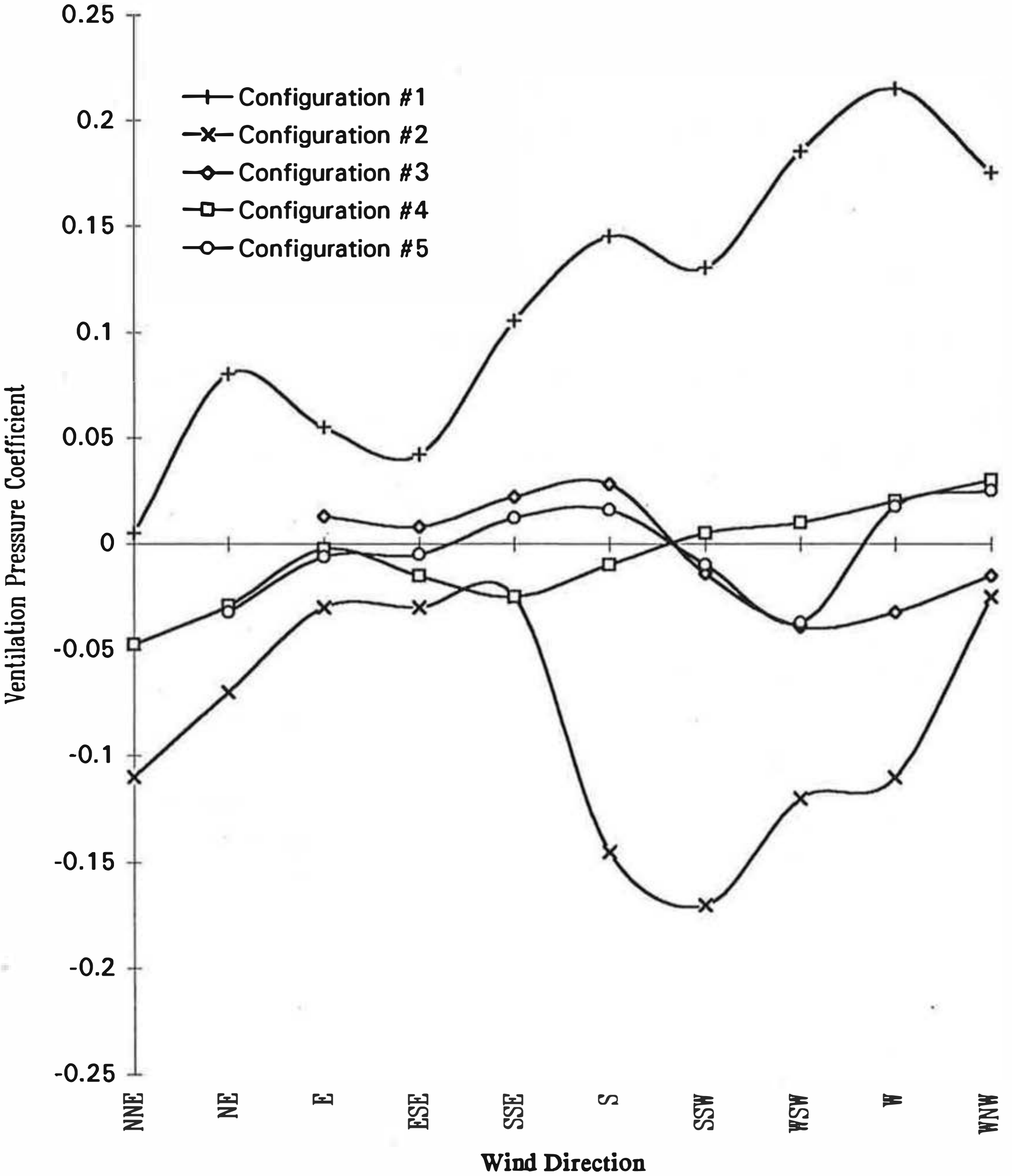


Figure 3.11c: Mean Ventilation Coefficients (All Directions and Configurations)

each wind direction for each of the five venting configurations. Appendix C contains statistical summary data and relative frequency plots for each venting configuration.

Several important conclusions can be drawn from these results. Vent configuration #1 (two vents separated vertically by 2.4 m) had by far the largest average ventilation coefficient (0.18) and was the only configuration in which the ventilation pressures always acted in one direction, regardless of the wind direction. These results justify the common belief that the best vent locations to encourage ventilation are at the top and bottom of the cavity.

The ventilation pressures for most venting configurations were higher for wind acting directly on the wall (west), but could still be significant when the wind came from the other direction (easterly wind direction). Hence, ventilation flow can occur even on the lee side of a building.

Consideration of the percentage of time that the wind acts from a certain direction and the average annual wind speed from that direction allows the calculation of mean annual ventilation pressures for the test walls in Beghut. In Figure 3.12 the ventilation *potential* for each orientation is plotted for the different configurations. The potential was calculated as the product of the ventilation coefficient, the mean wind speed, and the number of hours per year that the wind blows from this direction. The potential is expressed in units of pascal·hours per year and is valid for Waterloo, Ontario and the vent configurations tested on the Beghut.

It is clear from Figure 3.12 that some orientations, and some parts of a wall, will receive several hundred times more wind-driven ventilation than others and that the location of the vents on the wall can have almost as large an influence. In Waterloo, the wind is predominately from the west and hence walls exposed to the west receive the most wind-driven ventilation. In many cases, the predominant wind direction also brings the highest load of driving rain wetting. The leeward side of a building will usually have the highest amount of exfiltration condensation wetting however.

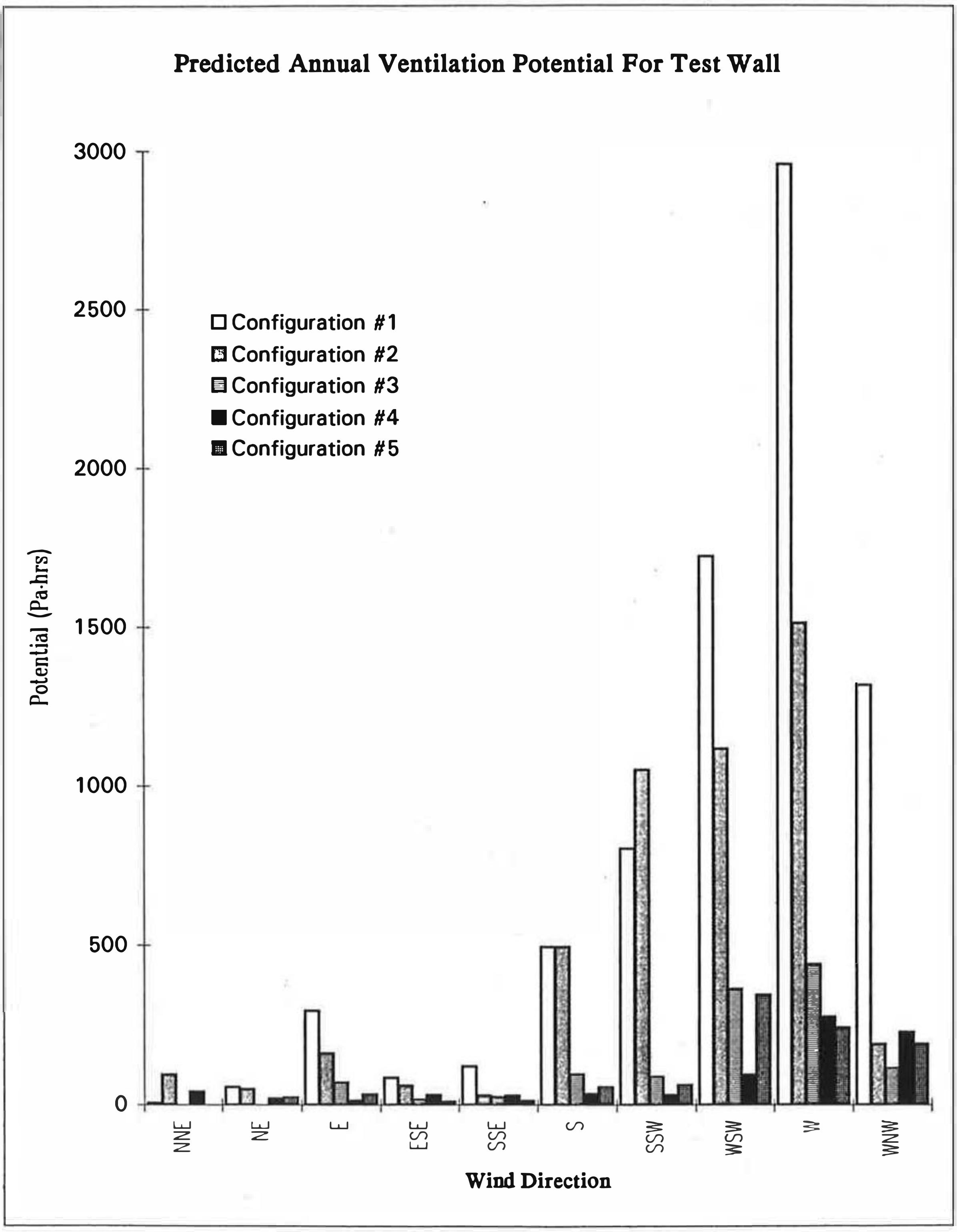


Figure 3.12: Ventilation Potential For Test Wall

3.2.3 Dynamic Spatial Variations

Short-duration (i.e., less than about 3-5 seconds) gusts can occur over small regions of a building and create temporary but large pressure gradients. We have yet to attempt to quantify the influence of these variations on ventilation, but some pertinent comments and observations can be made.

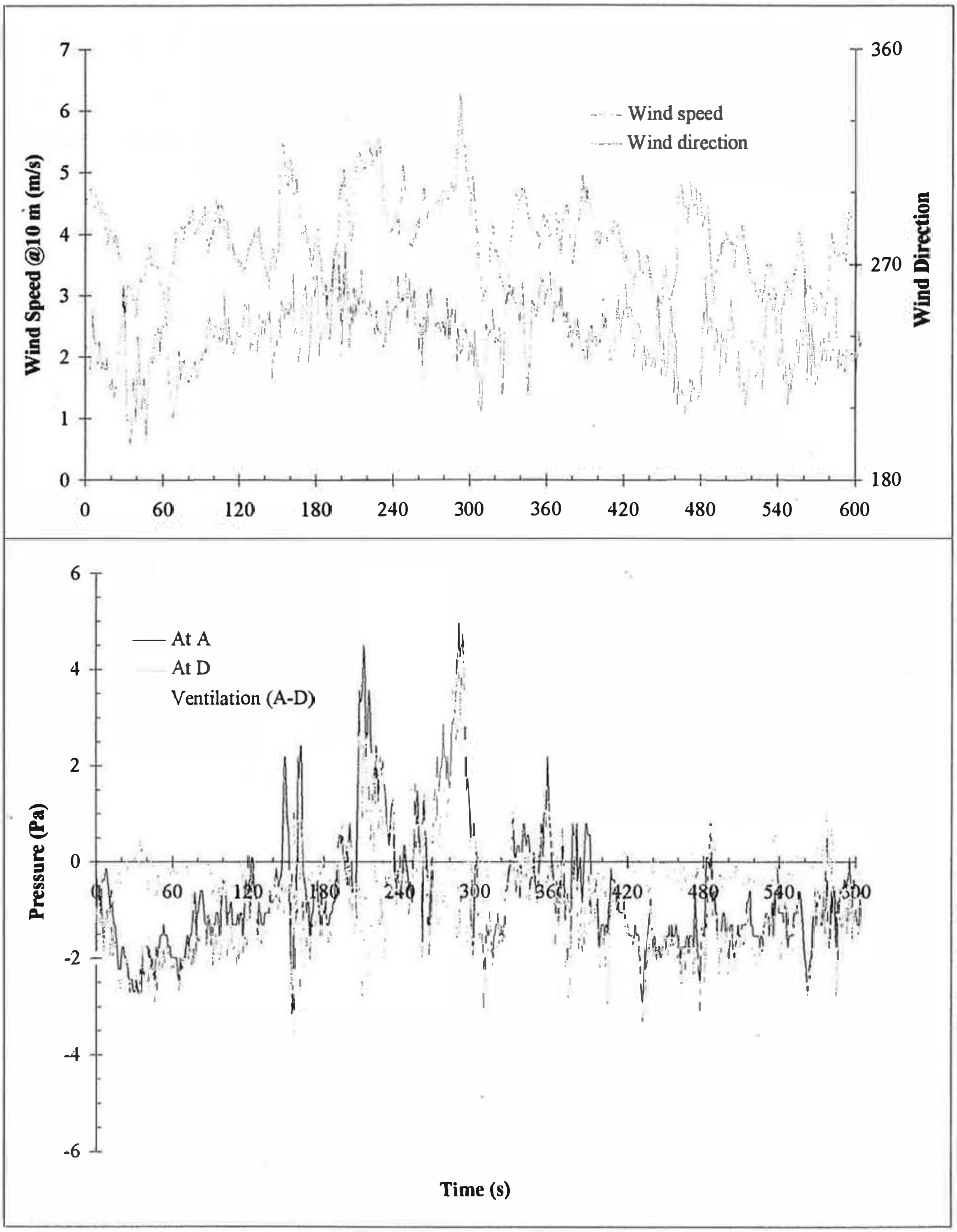
Figure 3.13 is a plot of measured wind and pressure for venting configuration #3. The wind speed and direction is very similar to the record presented in Figure 3.10. Note, however, the significant difference in pressure measured on the face of the building; the pressures are more variable and less well correlated. The pressures at A and D are often almost the same, but short-term dynamic spatial variations resulting in pressure differences are common. Although the average ventilation pressure is -0.34, Figure 3.13 shows that it is also sometimes positive.

One approach to assessing the influence of dynamic spatial variations is to use statistical measures of the variability of the ventilation pressures. For example, although the smallest ventilation coefficient for venting configuration #1 ($C_{p,v} = 0.007$ for wind from the NNE) suggests little ventilation action, the average standard deviation of the vent pressures for this direction category was 0.5 Pa. This indicates that the flow direction was constantly changing but still acting to ventilate the wall. Hence the average value is misleading, and the standard deviation provides a better measure of the likely ventilation potential.

As another example, consider the ventilation coefficients over all wind directions for venting configuration #5. Although these coefficients are quite small (in the order of 2-3%) and the average measured ventilation pressure was only -0.27 Pa, the average standard deviation was 1.82 Pascals (see Appendix C). This large variability is likely to force a significant amount of air movement through the cavity. In fact, the high standard deviation likely has just as significant an effect on ventilation flow as an average 1 Pa pressure difference.

The spatial extent of gusts is directly related to the wavelength of the wind (i.e., velocity ÷ frequency) and turbulence [41]. As the wavelength increases so does the size of the gust. For a given velocity, as frequency increases (i.e., the gust duration decreases) the size of the gust decreases. For a given frequency, as velocity increases so does the spatial extent of the gust. As turbulence increases, the size of the gusts decreases.

In a very simple analysis it is possible to postulate a 'gust size' from the statistical information collected from wind measurements. One suggestion is that a typical gust size in the wind will be of the order of 1/5 to 1/8 of the wavelength and somewhat smaller in more turbulent regions on building faces [42]. For a velocity of 10 m/s (a strong wind) and a gust duration of three



Note: Wind from West South West. Venting configuration #3. Avg. windspeed 3.8 m/s.

Figure 3.13: Example Ventilation Pressure, Stagnation Pressure, and Wind Speed Record

seconds, a typical gust size would be (1/8 to 1/5) · 10÷(1/3) = 4 to 6 m in size. For a 4 m/s wind (an average velocity), the same 3-second gust would have a size of 1.5 to 2.4 m. For a one-second duration gust under similar wind speed conditions, the gust size would be 1.25 to 2.0 and 0.5 to 0.8 m respectively. Therefore, short-duration gusts can realistically be expected to envelope only a few of the many vents in a well-vented wall system. Near building edges or on complicated geometries, the turbulence will be significant and the gust sizes will be relatively small.

If the gusts are large enough to simultaneously envelop all vents connected to a cavity, no ventilation will occur because the pressure acting on all vents will be similar. However, a short-duration gust acting over only one vent will force air into the cavity at the vent over which it acts. Although this may occur for a short time only, flow through the cavity can be significant. For walls with a single vent the compression of the air by temporal pressure variations is so small that little mixing can be expected (see 3.3.4).

Ventilation flow through windows is somewhat similar to building cavities in that spatio-temporal pressure variations drive the ventilation. Although difficult to predict, some research in this direction [43, 44] has shown that significant ventilation rates can be achieved by this mechanism alone.

3.2.4 Wind Pumping

A cavity with one vent hole can, to some extent, be "ventilated" by wind-induced pressures in a manner similar to thermal pumping. The changing wind pressures at the vent hole location will compress and decompress the volume of air in the cavity. Thus, a small volume or slug of air will move into and out of the cavity. Over the period of hours or days, the volume of air displaced will accumulate. However, only air near the vent hole itself is exchanged. Air has a very low vapour diffusion resistance and moisture in the cavity somewhere other than the vent hole can move rapidly to the vent hole by diffusion and convection (induced by both thermal and vapour differences throughout the cavity volume) within the cavity.

The change in volume due to compressibility (i.e., the volume of air exchange from pumping) because of an increase in exterior pressure can be calculated from Charles' Law as:

$$\Delta V_{pumping} = \frac{\Delta P}{P_{abs}} \cdot V_{cavity}$$

where V_{cavity} is the air volume of the cavity

ΔP is the pressure change

P_{abs} is the absolute atmospheric pressure (typically about 101 300 Pa)

The above relationship is based on the assumption that the volume of the cavity does not change. Flexible cavities (e.g. those with non-adhered membranes as air barriers) will allow a much greater volume of air movement.

Figure 3.14 plots the ventilation flow rate as a function of the gust rate. It can be seen from the measured pressures plotted in Figures 3.10 and 3.13 that the gust rate is much less than 100 Pa/s for the vast majority of the time. For gust rates of less than 100 Pa/second, the ventilation flow rate is very small, less than about 0.1 litres per second, and on average the pumping ventilation rate is likely to be less than 0.01 litres per second. These results have two implications.

First, a relatively small transfer of air takes place because of pumping; it is not a very efficient means of ventilation. Unless the cavity has a flexible wall (which is very detrimental to pressure moderation performance), the ventilation flow is unlikely to be beneficial.

Secondly, consider pressure moderation across the screen. The flow of air necessary to moderate a significant percentage of the pressures acting on the screen is very small. Flows of 0.1 lps are easily achieved through most wall vents with very little restriction and hence pressure drop (e.g., the pressure drop across an open head joint would be less than 0.1 Pascals). Higher gust rates, say 500 or 1000 Pa/s, which may occur for a few seconds per storm, will still only require flow rates of less than 1 litre per second to equalize pressures. These flow rates through an open head joint produce a pressure drop of about 3 Pa through an open head joint, i.e., only 0.3% of the applied pressure gust rate! Hence, if compressibility of the air were the limiting factor, the pressure variations that a PMS wall is exposed to could be well moderated – practically equalized – by small flows of air through relatively small vent areas. The degree of pressure moderation is generally controlled by the size of spatial pressure variations, not by the venting area. This unfortunately means that the level of pressure moderation can be increased by increasing compartmentalization (an expensive solution) and not simply by increasing vent area (a relatively inexpensive solution).

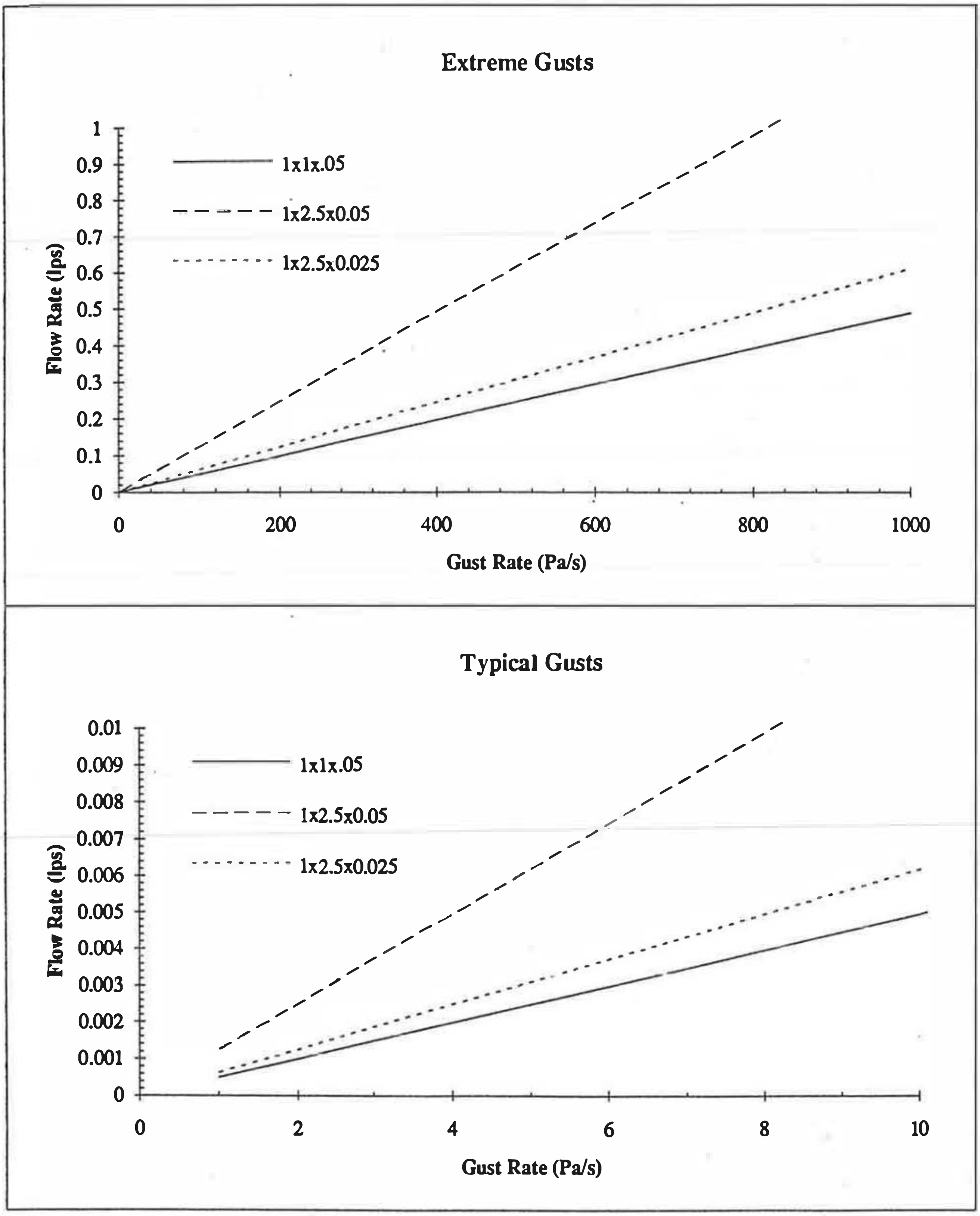


Figure 3.14: Air Flow as a Function of Gust Velocity

3.3 Other Forces

There are forces other than thermal and wind which can drive ventilation air flow. The most important of these are moisture buoyancy and air leakage.

3.3.1 Interior Pressures

If a building interior is pressurized or depressurized by building stack effect, mechanical ventilation, wind, or a combination of these forces, a faulty air barrier can allow a significant volume of air to flow through the envelope. However, the interior air will have a drying effect only in air conditioned buildings in the summer. In the winter, condensation can be expected to occur.

It is difficult to quantify the nature of a poorly constructed air barrier and to evaluate the effects of interior building pressures. For a 10 to 15 storey building, the combined pressures across the envelope could be of the order of 10 to 100 Pa [45]. The air barrier in high-rise residential structures may allow air flows through the envelope in the range of 0.5 to 10 $l/s/m^2$ at a pressure of 50 Pa [46] and this air must pass through the cavity and leave via the vents. Thus it can be seen that a leaky air barrier could result in the flow of a significant volume of air through the cavity. Since interior air is conditioned (and thus requires energy to replace) and may contain moisture, such mass flow must be seen as a significant potential moisture load on the wall.

Even though the difference in moisture content between the exterior and conditioned air is almost as large in the summer as in the winter, the pressure differences acting across the envelope tend to be significantly smaller in summer than in winter. Therefore, the potential for wintertime condensation is usually much larger than summertime evaporation. The nature of air leakage flow is also quite different from ventilation flow, which tends to be distributed over large areas. In general, air leakage flow is concentrated at rips, punctures, and other defects in the building envelope. While condensation can accumulate as frost along the leakage path, drainage of condensate will distribute moisture to larger areas of the envelope. Summertime exfiltration along the same path can only dry the surfaces that the air stream passes over, not the other parts of the assembly that may have wetted during the winter. For this, and other more technical reasons (the hysteresis of sorption isotherms and the nature of the energy transfer during evaporation and condensation), exfiltration evaporation will not be as efficient, and sometimes several times less efficient, a moisture transfer mechanism as exfiltration condensation. For very small volumes of air leakage, drying may occur, but not to the same extent as wetting under the opposite conditions of temperature and vapour pressure differences.

3.3.2 Moisture Buoyancy

As described in Section 3.1, temperature affects air density. The moisture content of air also affects the air density slightly. Air with water vapour has a lower density than dry air. Employing ideal gas law relationships [29], one can calculate the mass of air as:

$$w_a = \frac{p_a V}{R_a T}$$

and the density of water vapour as

$$w_w = \frac{p_w V}{R_{wv} T}$$

where

w_a and w_w are the mass of the dry air and water vapour (kg)

p_a and p_w are the partial pressures of dry air and water vapour (Pa)

V is the volume of moist air (m^3), and

R_a and R_{wv} are the gas constants for air (287.1 J/kg·K) and water vapour (461.5 J/kg·K)

The difference in density of two air masses at the same temperature but with different moisture contents can cause convective air flow within the cavity. Such convection is useful because it ensures that moisture is well distributed and mixed throughout the air in the cavity.

The difference in air moisture content between the cavity and the outside generates buoyancy forces which drive air flow in the same manner as thermal buoyancy (Figure 3.5). Table 3.2 contains the results of calculations of the pressure difference generated by moisture buoyancy alone in wall cavities of different heights with a saturated inner wythe (i.e., 100% RH) as a function of the difference in air temperature and outdoor relative humidity. For convenience, the inner face of the cavity temperature has been assumed to be at a temperature of 10°C. For the case where the outside temperature is 3°C cooler than in a 2.4 m high cavity , a driving pressure of about 0.3 to 0.4 Pa would be generated for typical outdoor relative humidities of between 50 and 85%. If the outdoor air is 30°C cooler (e.g., a cool but sunny day), pressures of 3.6 Pa would be generated, even with outdoor humidities of 85%.

A comparison of these results to the thermal buoyancy results in Table 3.1 shows that moisture buoyancy can be as large a ventilation driving force. While thermal buoyancy will act whenever the cavity temperature is greater than ambient, moisture buoyancy occurs only when the cavity air has a higher moisture content than the ambient, i.e., the cavity is wet and evaporating vapour into the cavity air. On a calm sunny day in the spring or fall, a wall with a wet screen or inner wythe may often be subject to combined moisture and thermal buoyancy pressures of more than 5 Pa. The moisture buoyancy pressures will steadily decrease as the inner wythe or screen dries and increase dramatically under solar heating. Naturally, as evaporation rates increase, the temperature of the drying surface will decrease because of the energy of evaporation.

For 10°C cavity temp.	*Temperature Difference (Cavity - Exterior)*					
	ΔT= 3 °C Outdoor RH		ΔT= 10 °C Outdoor RH		ΔT= 30 °C Outdoor RH	
Cavity Height (m)	50% ΔP (Pa)	85% ΔP (Pa)	50% ΔP (Pa)	85% ΔP (Pa)	50% ΔP (Pa)	85% ΔP (Pa)
2.4	0.39	0.35	1.17	1.15	3.60	3.60
3.0	0.49	0.44	1.47	1.44	4.50	4.50
3.6	0.59	0.53	1.76	1.72	5.41	5.40
4.8	0.79	0.71	2.35	2.30	7.21	7.20
6.0	0.98	0.89	2.93	2.87	9.01	9.00

Table 3.2: Calculated Ventilation Pressures Due to Moisture Buoyancy

4. Ventilation Flow Mechanics

In this chapter, basic flow mechanics theory is applied to air flow through vents and cavities. The previous chapter outlined the potential driving forces and their magnitude (in Pascals). This chapter considers the resistance to ventilation flow (friction in various forms) in the form of pressure losses (in Pascals). A ventilation flow system balances the driving forces and the resisting forces.

Figure 4.1 presents a simplification of ventilation flow mechanics through a wall cavity (either vertically or horizontally). The resistance to flow from points A to B and C to D is due to the vents. From points B to C, the flow resistance is due to friction with the cavity walls.

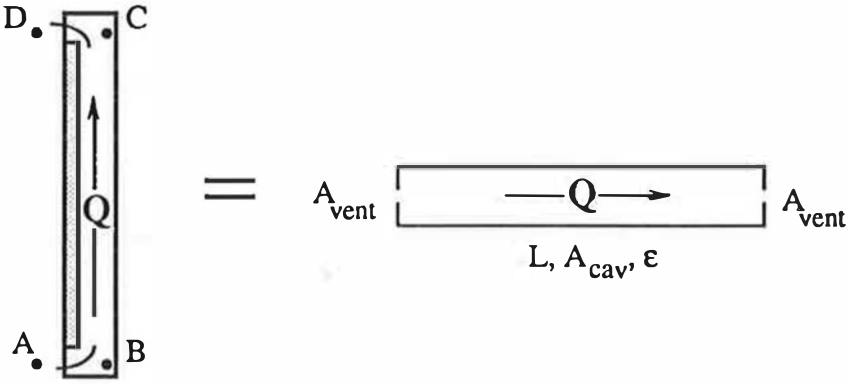


Figure 4.1: Flow Resistance Model of a Cavity

Ventilation flow can be seen to be analogous to flow through an orifice into a rectangular duct and out again through an orifice. Predicting the resistance to ventilation air flow in this simplified model is developed by first examining the flow through the cavity and then the flow through the vents.

4.1 Air Flow in Cavities

Resistance to air flow in the cavity (between points B and C in Figure 4.1) is theoretically dependent primarily on three characteristics:

1. flow velocity
2. roughness of the sides, and
3. the size (depth) and shape of the cavity.

In practice, a fourth characteristic, the number and size of obstructions and degree of baffling, can be very important. Because this fourth characteristic depends mostly on workmanship, it is difficult to quantify. Nevertheless, it is dealt with below.

Friction varies significantly with velocity – the friction depends on whether the flow is laminar or turbulent. In laminar flow the shear between particles causes the air to flow smoothly. In turbulent flow, the inertia of individual air particles exceeds the shear between particles. For internal flows (flow where the air is confined on all sides) the transition between laminar and turbulent flow occurs when the Reynolds number lies between 2000 to 3000. The Reynolds number is a dimensionless measure of the ratio of viscous to inertial forces. For standard air conditions the Reynolds number can be found from the following equation [29]:

$$Re = 66\,400 \cdot D_h \cdot V$$

where, Re is the Reynolds number, D_h is the hydraulic diameter (or equivalent diameter), and V is the velocity of the flow

The hydraulic diameter of a cavity can be defined as:

$$D_h = \frac{4 \cdot A}{P} \ ,$$

where $A = b \cdot d$ is the cross sectional area and $P = 2 \cdot d$ is the perimeter of a cavity b wide and d deep. Therefore, for a cavity the hydraulic diameter is

$$D_h = 4\ b \cdot d \div 2\ b = 2\ d$$

Figure 4.2 shows plots of the flow rate through cavities and vents versus the Reynolds number and indicates those regions of flow velocity or flow rate that are laminar and those that are turbulent. This plot shows that flow can normally be assumed to be laminar over the typical velocities expected in cavity ventilation. In laminar flow, the pressure drop across the cavity will vary linearly with velocity. If the flow increases sufficiently, it becomes turbulent and friction will then increase faster than flow rate. This has the benefit of naturally limiting ventilation flows to velocities that are less likely to entrain water into the cavity.

The Darcy-Weisbach equation is commonly used [23] to give the pressure drop due to friction in fluid flow through pipes and airflow through ducts:

$$\Delta P_{pipe} = f \cdot (L / D_h) \cdot P_v$$

where f is the friction factor (this accounts for flow velocity and pipe roughness),

L is the length of the pipe, D_h is the hydraulic diameter, and

P_v is the velocity pressure of the air flow, which can be calculated as

$$P_v = 0.5 \cdot \rho \cdot V^2 = 0.6 \cdot V^2 \ \text{for} \ \rho_{air} = 1.2 \text{ kg/m}^3$$

For laminar flow the friction factor varies simply with the flow rate but also depends on the shape of the duct. For the two extremes of shape [31,47]:

$f = 64/(Re \cdot \gamma)$, circular ducts, and

$f = 96/(Re \cdot \gamma)$, channel flow (as in a cavity).

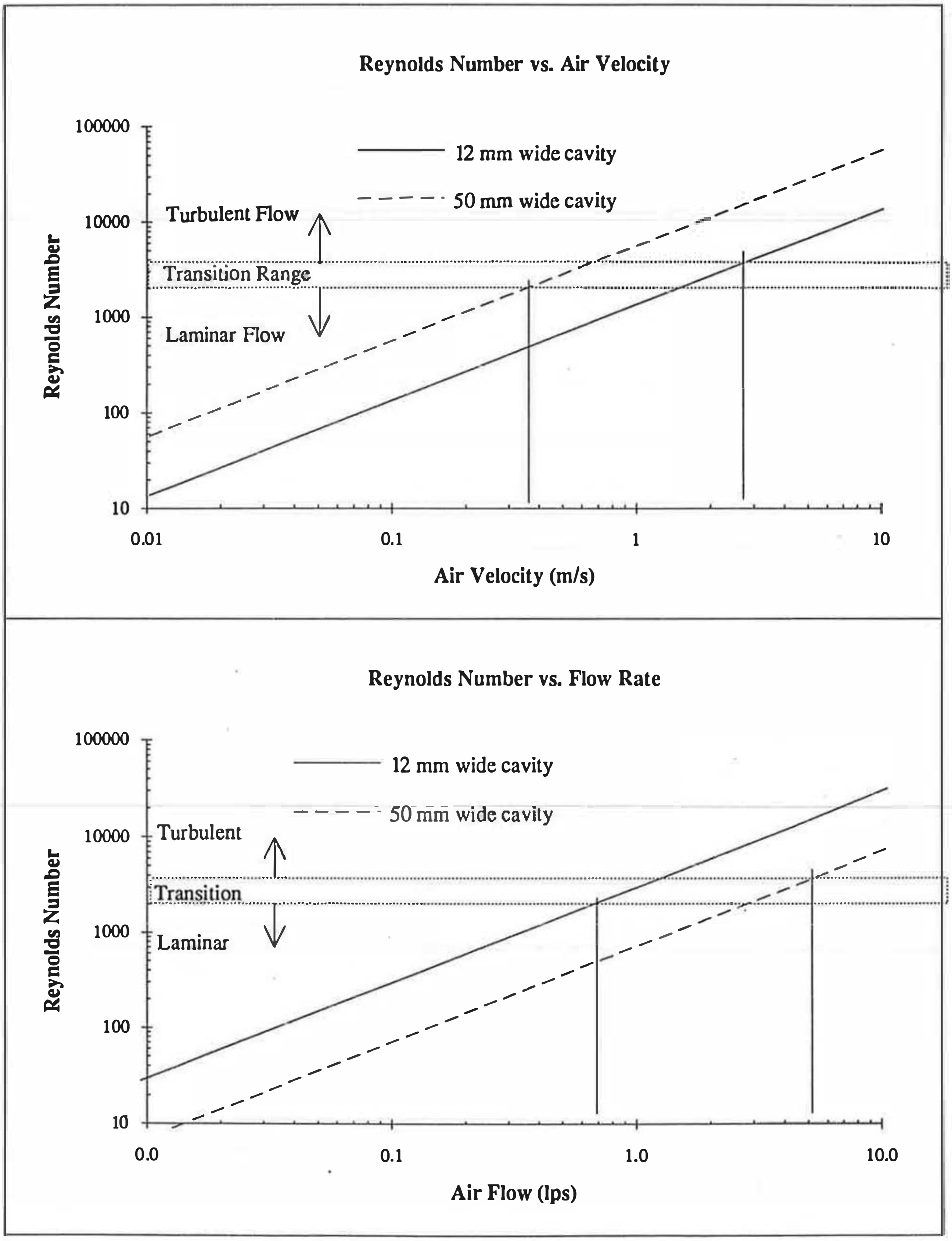


Figure 4.2: Laminar and Turbulent Flow Ranges in Wall Cavities

A blockage factor, γ, has been included to account for very rough and/or partially obstructed cavities. This factor is approximately equal to the average reduction in cross-sectional area caused by the protrusions from the side of the cavity. For clear cavities $\gamma=1$. For cavities with small protrusions, say the mortar from bed joints in a carefully constructed brick veneer or a stone veneer with the normal number of anchors, a γ value of 0.8 might be appropriate. Since many brick veneers have partially blocked cavities, the value of γ may be significantly less than this.

For turbulent flow, the friction factor varies considerably with flow and roughness. However, a simplified approximation developed by Altshul-Tsal [29] is:

$$f = 0.11 \cdot \left(\frac{\varepsilon}{D_h} + \frac{68}{Re}\right)^{0.25}, \text{ for } f > 0.018$$

where ε is the absolute roughness. This is defined as the average height of projection divided by cavity width.

D_h is the equivalent diameter of the duct and Re the Reynolds number.

For ventilation flow through an enclosed cavity, it can be assumed that the flow will be laminar. Flow velocity is merely flow volume divided by flow area (V= Q/A). Combining equations, therefore, the pressure loss of laminar air flow through a wall cavity can be estimated as:

$$\Delta P_{cavity} = \frac{V \cdot h}{692 \cdot \gamma \cdot D_h^2} = \frac{Q \cdot h}{4610 \cdot \gamma \cdot b \cdot d^3}$$

where d is the cavity depth,

h is the cavity height,

b is the cavity width,

γ is a blockage factor, and

Q is the flow volume (all in consistent units).

4.2 Flow Through Vents

Two typical building-related cases should be considered: discrete vents that act as orifices, and continuous slots. Using the standard sharp-edged orifice flow coefficient, the pressure drop across a vent hole acting as an orifice can be calculated as:

$$\Delta P_{vent} = \left(\frac{Q}{0.65 \cdot A_{vent}}\right)^2$$

Chapter 2 dealt with theoretical and measured vent flow behaviour and should be referred to and different flow coefficients and exponents substituted in the equation for more accuracy.

The change in direction from horizontal to vertical flow is not likely to be a significant factor for most ventilation flow situations because the flow velocity is so slow. Although this assumption needs to be proven, it is based on the observation that discrete vents provide such a large proportion of the total flow resistance in walls that the resistance to a direction change in an open cavity is, in relative terms, not significant. A small increase in flow resistance (in the order of 10% of vent resistance) might be in order for high entrance flows, whereas at very low flows (typical ventilation conditions) no increase would be necessary.

4.3 Flow Through Slots

For the situation where a continuous (or semi-continuous) slot is provided as a vent, the cavity tends to provide a significant proportion of the flow resistance, and the change in direction at the vent becomes important. Based on European research [7, 9, 47] and North American HVAC practice [29], the following approach is suggested.

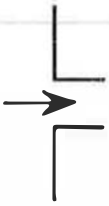
Losses are based on a fraction of the dynamic velocity pressure as:

$$\Delta P_{slot} = f\,(L / D_h) \cdot P_v = \xi \cdot P_v = \xi \cdot (0.5 \cdot \rho \cdot V^2)$$

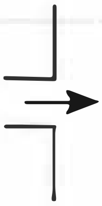
$$= \xi \cdot 0.6 \cdot V^2 = \xi \cdot 0.6 \cdot \left(\frac{Q}{b \cdot d}\right)^2$$

where ξ is a friction factor, V is the flow velocity, and $\rho_{air} = 1.2$ kg/m^3. The flow velocity is referenced to the flow in the venting slot, not the flow velocity in the cavity.

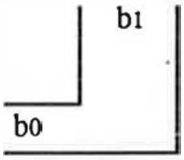
The following values of ξ have long been used in practice by European designers [7, 9]:



Entrance:
$\xi = 0.5$



Exit:
$\xi = 0.88$



Rectangular Elbow:

$\xi = 0.885 \cdot (b1/b0)^{-0.86}$

4.4 Wall System Flow

At equilibrium, the pressure drop across two vent holes and cavity will equal the pressure drop due to external driving forces, or

$$\Delta P_{drive} = \Delta P_{vent,entrance} + \Delta P_{cavity} + \Delta\ P_{vent,exit}$$

For many **wall systems with discrete vents and laminar flow** the entrance and exit vents will be of the same type and can be lumped together (for other systems the flow may enter and leave via different vent types) and the above equations simplified to:

$$\Delta P_{drive} = 2 \cdot \Delta P_{vent} + \Delta P_{cavity} = 2 \cdot \left(\frac{Q}{0.62 \cdot A_{vent}}\right)^2 + \frac{Q \cdot h}{4610 \cdot \gamma \cdot b \cdot d^3}$$

In the case of discrete vents, the value of b is the horizontal spacing between vents.

For a **panel system with continuous open slots:**

$$\Delta P_{drive} = \Delta P_{slot} + \Delta P_{cavity}$$

$$= \xi \cdot 0.6 \cdot \left(\frac{Q}{b \cdot d}\right)^2 + \frac{Q \cdot h}{4610 \cdot b \cdot d^3}$$

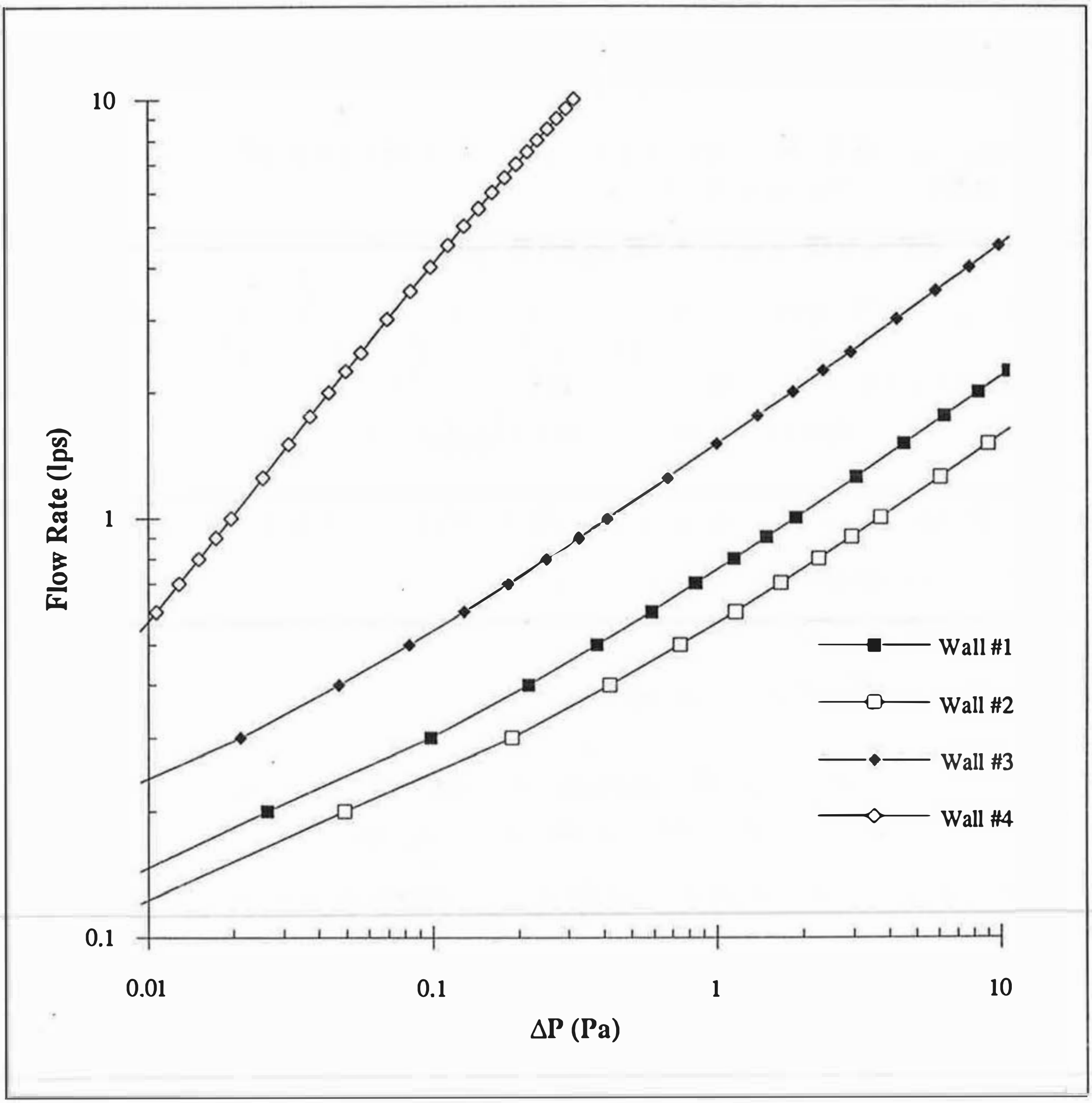
where, assuming the same slot at the top and bottom of the cavity, the slot entrance, exit, and direction change resistance can be lumped together as

$\xi = 0.5 + 2 \cdot \{0.885 \cdot (d/d_s)^{-0.86} + .88\}$, d_s is the slot height

In the case of a panel system with slots b can be chosen as either a unit width or the width of one panel.

Therefore, with a knowledge of the driving forces and the characteristics of the wall system, the ventilation flow can readily be calculated. Figure 4.3 shows plots for the flow rate through the cavities of typical wall systems and a likely range of driving forces. A blockage factor of 1, relatively unlikely in brick veneer walls, has used to generate Figure 4.3.

Walls # 1 and #2 in Figure 4.3 represent ideal versions of walls that are presently being built. Because of blockage, the flow rates are likely to be smaller than shown. Wall #3 represents a wall built to increase ventilation; vent area is three times as large as normal and the cavity is twice as deep (to reduce the chance of blockage). It can be seen that the flow through this wall is at least twice as much as Walls #1 and #2. Wall #4 represents a panel cladding system applied to a five-storey building. The ventilation flow through the cavity of this system is more than ten times the flow through a typical brick veneer wall.



Clear Cavity and Vents Assumed.

Wall #1: 2.4 m high, 25 mm deep cavity, full-width 12 mm slot top and 10 x 65 vent @ 600 bottom
Wall #2: 2.4 m high, 25 mm deep cavity, 10 x 65 vent @ 600 o.c. top and bottom
Wall #3: 2.4 m high, 50 mm deep cavity, 10 x 65 vent @ 200 o.c. top and bottom
Wall #4: 12 m high (5 stories), 50 mm deep cavity, full-width 12 mm slot top and bottom

Figure 4.3: Ventilation Flow versus Driving Pressure in Some Typical Walls

5. Ventilation Drying

5.1 Moisture

To develop some understanding of how and how much moisture that can be removed from a wall by ventilation, it is useful to review the fundamental behaviour of moisture in walls and the drying process in general. This chapter briefly considers the sources of moisture, the available storage, and the mechanisms of moisture removal.

5.1.1 Moisture Sources

Moisture can be present in a wall cavity in vapour, liquid, and solid forms from three basic sources:

- rain (or precipitation) penetration or absorption,
- condensation from diffusion and air movement through the wall, from both the interior and exterior, and
- moisture built-in during construction.

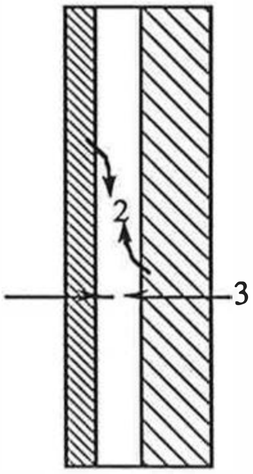


Figure 5.1: Cavity Moisture Accumulation Mechanisms in Screened Walls

Moisture can *enter* a wall cavity by means of the following general mechanisms (Figure 5.1):

1. penetration of the screen by rainwater (or melted snow and ice) ,
2. desorption of built-in and stored moisture from materials within the wall assembly (especially the screen), and

1 & 3. vapour diffusion and air movement into the cavity from the interior or exterior environments.

5.1.2 Moisture Storage

Moisture can be *stored* in or near the cavity in a variety of ways (Figure 5.2):

1. as water trapped in small depressions in the mortar droppings of BV walls or poorly drained portions of other types of walls;
2. as droplets (or frost) adhered by surface tension to the backside of the screen or front side of the inner wythe;
3. adsorbed, or retained by capillarity, in hygroscopic building materials (especially brick, wood, fibrous insulation, paper, etc.) which form the sides of the cavity; and
4. in the cavity air as vapour.

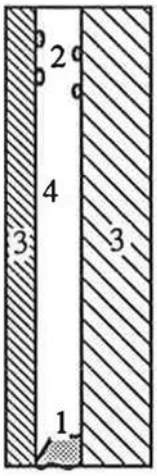


Figure 5.2: Moisture Storage in Cavities of Screened Walls

The volume of water that is stored in a wall can be large, in the order of several kg per square metre. If the volume of this stored water exceeds the safe level for a material and is present for long enough, deterioration can occur, i.e., rotting of wood, freeze-thaw damage of masonry, and corrosion of metal.

5.1.3 Moisture Removal

Moisture can be removed from the cavity and adjoining materials in a variety of ways (Figure 5.3):

1. drainage, driven by gravity
2. evaporation from the outer surface of the screen
3. diffusion and air leakage outward through the screen, and inward into the wall or building interior
4. mass flow of the cavity air; ventilation, and
5. capillary transport to drier adjoining materials

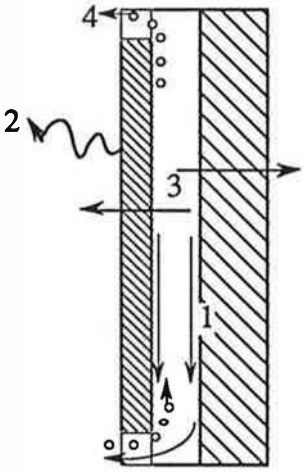


Figure 5.3: Moisture Removal Mechanisms for Cavities in Screened Walls

Drainage can remove the greatest volume of water in the shortest time and is obviously the most important mechanism for moisture control in screened wall systems. Provided a clear path exists, a large proportion of any penetrating water will flow out of the wall cavity. However, even in perfectly constructed walls, a significant volume of water will remain attached by surface tension to the cavity sides and on wall anchors, etc., and be trapped in countless small mortar dams, bridges, droppings and depressions. The materials forming the cavity (e.g., mortar, brick, sheathing) will also absorb and store significant volumes of water. Condensation will tend to deposit moisture slowly and therefore allow the material on which condensation occurs (e.g., gypsum sheathing or waferboard), time to absorb the deposited moisture. In this situation, the cladding or sheathing must be virtually saturated before sufficient volumes of water will bead on the surface enabling drainage to occur. Therefore, it must be assumed all the moisture stored or deposited in the cavity will not be removed by drainage alone.

The moisture in saturated screens can evaporate to the exterior, but evaporation can take a long time for some screen materials (wood, brick). Evaporation from brickwork can remove significant volumes of moisture; theoretical calculations and laboratory experiments suggest rates of 200 to 300 g/m^2/hr are possible[48]. Lacy [49] measured evaporation rates from brickwork in the field and reported maximum rates of 68 g/m^2/hr for a few hours, 20 g/m^2/hr for a few days, and 1- 7 g/m^2/hr for most of the time (when the walls were likely not saturated). Schwarz measured rates of between 50 and 200 g/m^2/hr (depending on the influence of solar heating and wind speed) immediately after driving rain [50]. Note that evaporation rates are likely to be similar for wood, concrete, and stone claddings because all are in Stage I drying. Unfortunately, most evaporation occurs from the outside face, and the inner side of the brick will remains wet for longer. Solar heating of the screen (especially brickwork) can often cause evaporation from the inner face and condensation on the inside face of the cavity [51-53]. This wetting of the cavity's inner face can be removed only by diffusion, ventilation, and, in extreme cases of saturation, drainage.

For walls with high vapour resistance cladding, the diffusion resistance will greatly retard drying of the inner wythe. Ventilation is important because it is a mechanism capable of removing moisture that remains behind screens with a high water vapour resistance.

5.2 The Drying Process

Hygroscopic materials in wall cavities dry by the processes of evaporation and desorption. The free water in the material is removed first by evaporation of liquid water at the surface of the material. Water evaporated from the surface is replaced by water that moves through the material toward the relatively drier surface. Once the material is no longer saturated, desorption begins [54, 55]. The rate of free water evaporation is much higher than the rate of desorption. The two processes and their different rates result in a moisture flux (or drying rate) with two fairly distinct stages (Figure 5.4) [48, 50]:

> Stage I is the surface-saturated rate of drying. It is believed that this rate is approximately the same as free-water evaporation under the same conditions and constant; hence it does not vary significantly from material to material.
>
> Stage II is the desorption drying rate. This rate is controlled by the material properties, surface-to-volume ratio, and the surrounding air conditions as described by the sorption isotherm. The rate decreases as the material approaches equilibrium with its environment

In a wall cavity, drying during both stages will be affected by [56, 57]:

- the volume, various degrees of wetting/saturation, and the distribution of different materials and different parts of the wall assembly,

- the amount and nature of moisture flow into the wall (by airflow, diffusion, or rainfall)
- the temperature and vapour pressure conditions and gradients,
- the different sorption isotherms of the hygroscopic materials,
- the vapour resistance of different layers in the wall assembly,
- the rate of air flow through the cavity, and
- the exterior ambient air conditions.

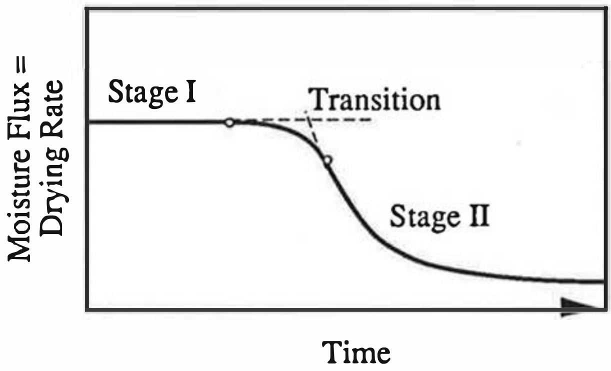


Figure 5.4 Drying Stages for a Saturated Hygroscopic Material

Although the rate of Stage I drying is probably the same as free water under the same conditions [48, 50], evaluating the evaporation rate of free water is also difficult. For some materials, geometries, and conditions of surrounding air, the transport of water through the saturated material may not replace the surface water as quickly as it is removed by evaporation; in such rare cases, the flow of water through the material will control the Stage I drying. Provided that free water is available over a constant surface area, the Stage I drying rate will remain approximately constant with constant air temperature and vapour pressure. The Stage II drying rate generally follows an exponential decay for constant air temperature and vapour pressure.

Consideration of the two drying stages leads to the expectation that wall cavities that are initially saturated will exhibit an initially high and constant rate of drying (as all free and surface water is evaporated) and an exponentially decreasing drying rate as all hygroscopic materials in the wall cavity approach their equilibrium moisture content. Between these two extremes there will be a transition in which drying is due to a combination of the two stages.

Constant air temperature and vapour pressure conditions are not common in the natural environment, and in a wall cavity conditions might be characterized as "constant" for a few hours at most. During the day, solar radiation may change the temperature of the screen so quickly that even an hourly average is not sufficiently accurate to capture the full range of behaviour. The expected environmental variations can be superimposed on the hypothetical drying figure to gain an idea of the form of a drying diagram.

5.2.1 Water Vapour Transport: Diffusion

Fick's Law governs the diffusion of vapour through any material (including air). The mass of vapour diffusing through a unit area in unit time (w) can be found as:

$$w = -\mu \frac{dp}{dx}$$

where μ is the permeability (a material property), p is the vapour pressure, and x is the distance along the flow path.

Diffusion through a multi-layer system can be estimated using a total calculated vapour resistance in exactly the same way as for heat flow. In practical situations, Fick's Law is normally simplified to:

$$m_w = \frac{1}{\mu_1 \ldots + \mu_x \ldots + \mu_n} \cdot \Delta P_v \cdot A \cdot \Delta t$$

where, m_w is the mass of water vapour transferred,

μ_x is the average vapour permeability of layer number x,

ΔP_v is the vapour pressure difference, A is the area, and Δt is the time.

Vapour flowing from a drying surface to the air must overcome a mass transfer surface film resistance. The magnitude of this surface film coefficient is not well known for the pure diffusive case but has been reported as between 1.34×10^{-5} g/N·s for saturated earth in a subfloor crawl space and 2.5×10^{-5} g/N·s for swimming pools during calms [58] and between 1.7 and 10.2 $\times 10^{-5}$ g/N·s for saturated wall samples exposed to wind speeds of 1 to 8 m/s [50]. In laboratory vapour permeability tests, Burch [59] found a film water vapour transfer coefficient of 2.874×10^{-6} g/N·s; this is an order of magnitude less, probably because he was able to avoid all thermally- and moisture-induced convective air flow over the surface. The Lewis Correlation, described later, can be used to estimate the value of the mass transfer coefficient for many geometric, temperature, and flow conditions.

As described above, during the first stage of drying, given a mass transfer surface film coefficient, g, the mass transfer due to diffusion alone from a wet surface to a building cavity can be approximated as:

$$m_w = g \cdot A \cdot \Delta P \cdot \Delta t$$

where, m_w is the total mass of water vapour transported

A is the area of wet surface, ΔP is the vapour pressure drive, and Δt the time interval

In stagnant air, the mass transfer calculated by the above equation might be substantially reduced by the vapour resistance of the air itself, and by the effect of evaporating water increasing the vapour pressure of air near the surface and reducing the temperature of the evaporating surface.

Diffusion is usually driven by a difference in vapour pressure (although it can also be driven along a temperature gradient). The pressure difference normally considered is the difference in vapour pressure across the envelope, i.e., the difference between interior and exterior environments. In some cases, normally when the wall is wet, the vapour pressure difference between some part of the envelope assembly (especially the screen) and either another part of the envelope (usually the inner wythe) or the interior or exterior environments is important (see Section 5.1.3).

5.2.2 Water Vapour Transport : Mass Flow

Moisture transport from a free surface by pure diffusion is unlikely to occur in most situations since some air flow is always present, either because of driving forces from outside the system or because the evaporation induces temperature and vapour gradients that result in air flow.

The exchange of air next to a drying surface and the mass flow of air across the surface of a material can greatly increase the rate of drying. The mass flow can accelerate drying because of two effects:

- exchanging the air surrounding a drying material with dry air ensures that the vapour pressure difference (and hence drying rate) will remain the same. Perfect mixing is a general assumption in a building cavity with mass flow, but the validity of this assumption depends on the vapour pressure differentials, mass flow rate, and cavity geometry.
- moving air over a surface essentially eliminates the resistance of air to diffusion and only the surface film resistance remains. The surface film resistance is much lower with air flow than in stagnant air.

Air Exchange

The process of moisture movement (at a known evaporation or desorption rate) from cavity materials to a well-mixed chamber can be represented schematically as in Figure 5.5. A well-mixed chamber is a reasonable assumption because of the internal convection that is likely to occur as a result of temperature and moisture buoyancy and the relatively low vapour diffusion resistance of air. This mixing is one of the reasons ventilation air flow is a far more effective drying mechanism than air leakage.

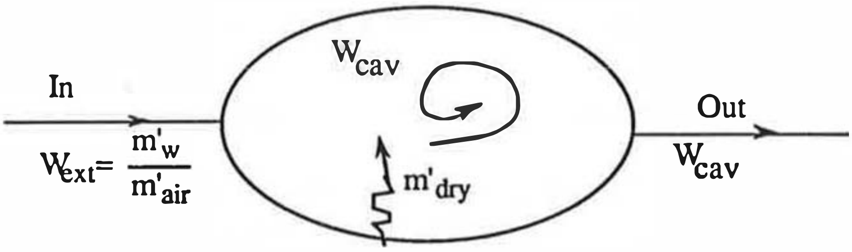


Figure 5.5: Simple Mixing Chamber Model of Cavity

The flow rate of vapour into the cavity (from the exterior air or, perhaps, from exfiltration of interior air) plus the flow rate of vapour because of drying will determine the water vapour balance of the cavity and therefore the driving potential for further drying. In terms of mass fractions (i.e. humidity ratios):

$$W_{cav} = \frac{(W_{ext} \cdot m'_{air} + m'_{dry})}{m'_{air}} \cdot \frac{\Delta t}{\Delta t} = W_{ext} + \frac{m'_{dry}}{m'_{air}}$$

where W_{cav} is the humidity ratio of the cavity air (kg water/kg air),
W_{ext} is the humidity ratio of the exterior or ventilating air (kg water/kg air),
m'_w is the mass flow rate of water vapour in the ventilating air (kg water /time),
m'_{air} is the mass flow rate of ventilating air (kg air /time), and
m'_{dry} is the drying rate of the ensemble of cavity materials (kg water /time),

The consideration of simple mixing allows calculations to be made which relate the ventilation rate and drying rate to the difference in humidity ratio between the cavity and outdoor air.

Air Flow Over A Surface

The flow of air in a cavity encourages drying of the cavity because flowing air increases the transfer of moisture from a wet surface to the air. The accelerated drying caused by air flowing over a surface can be calculated by using the Lewis correlation [29, 54] of heat transfer - mass transfer analogy. The surface vapour flow resistance can be defined in terms of the convective heat loss coefficient, h_{conv}, as:

$$g = \frac{h_{conv}}{R_v \cdot T \cdot \rho \cdot c_p}$$

where R_v is the gas constant for water vapour, T is the absolute temperature,

ρ is the air density, and c_p is the specific heat capacity of air.

This relationship is very useful because h_{conv} has been defined theoretically and empirically for a wide variety of flow conditions and geometries, whereas the mass transfer coefficient, g, is known for only a few cases. Although some research [59] suggests that the Lewis Correlation is not perfectly true for laminar flow (i.e., typical building cavity situations) it is still a relatively accurate approximation.

Heat transfer coefficients depend primarily on the flow velocity (Reynolds number), the flow regime (laminar or turbulent), the properties of the gas (Prandtl number), and the geometry of the flow channel [60]. A heat transfer relationship for forced convection of air in the laminar flow regime between parallel plates [61] is:

$$h_{conv} = 3.66 + \frac{0.104 \cdot Re \cdot Pr \cdot D / L}{1 + 0.016\,(Re \cdot Pr \cdot D / L)^{0.8}}$$

where, h_{conv} is the convective heat transfer coefficient,

Re and Pr are the dimensionless Reynolds and Prandtl numbers respectively,

D is the hydraulic diameter (twice the cavity width), and

L is the length of the flow path.

Using the Lewis correlation, the moisture transfer coefficient, g, can be found as:

$$g = \frac{h_{conv}}{R_{wv} \cdot T \cdot \rho \cdot c_p} = \frac{h_{conv}}{0.4615 \cdot 283 \cdot 1200 \cdot 0.00103}$$

For Reynolds numbers of 10 to 2300 (i.e., laminar flow) the moisture film transfer coefficient predicted by the above relationship is between about 6 and 12 x 10^{-3} g/s·m^2·Pa for cavities between 25 to 50 mm wide and 2.5 m high at normal temperatures.

Note that, not surprisingly, the mass transfer of water from a surface exposed to air flow is much greater than that for stagnant air (which is in the range of 1.5 x 10^{-5}). For example, the transfer of moisture from a completely saturated cavity wall at 20°C ($P_{v,sat}$ = 2300 Pa) to cavity air at 19°C and 80% RH (P_v = 1650 Pa) would be 6 · x 10^{-3} · (2300 - 1650) = 3.9 g/s/m^2 or 14 kg/hr/m^2! Naturally, the air flow through the cavity is insufficient to carry all of this evaporated moisture away and the RH of the cavity eventually reaches equilibrium with the wetted face of the cavity. The energy required to evaporate this moisture will also not generally be available. High rates of evaporation will also cause a significant drop in surface temperature and a consequent reduction in evaporation rate.

These calculations lead to the important conclusion that:

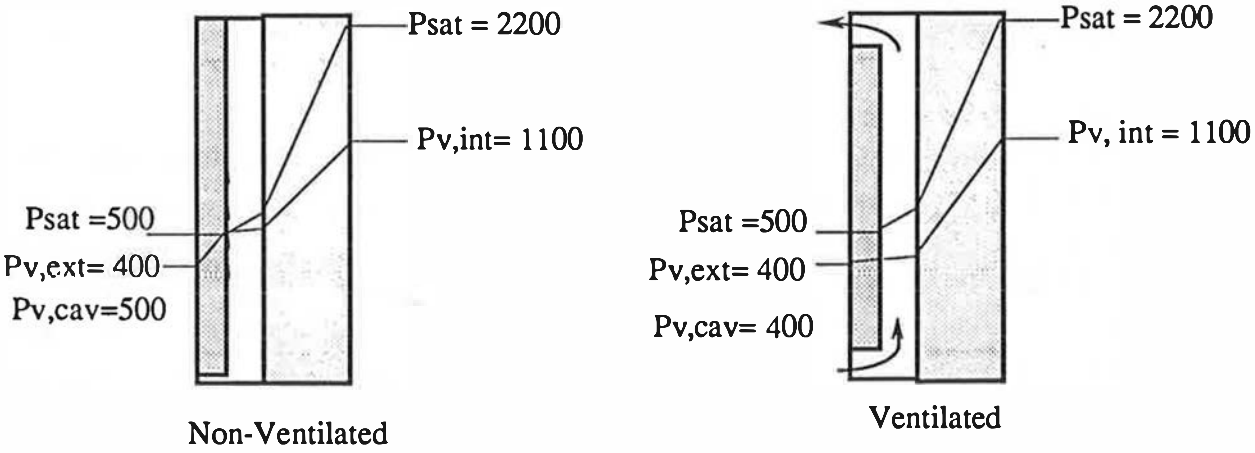
> **Because the transfer rate of moisture from a wetted surface to the air is high, and the volume of air in the cavity is low, it follows that for all practical building cavity situations, the rate at which moisture can be removed from the materials forming the cavity will be dictated by the rate at which moisture in the air leaves the cavity .**

This will be true for the initial portion of Stage 2 drying as well as Stage 1 drying.

5.3 Equivalent Vapour Permeance

The potential of ventilation is important to screened cavity walls because the screen often has a relatively high vapour resistance (e.g., brickwork, inorganic siding, steel, and stone). It is important to note that air flow can be a much more powerful water-vapour transport mechanism than diffusion. The concept of an equivalent water-vapour permeance of a cavity with an air exchange rate is very useful for assessing the potential effectiveness of ventilation – an equivalent vapour permeance is derived below for combined mass and diffusion transport.

The relative importance of mass flow for moisture transport through the screen of a screened wall can be judged by assessing the expected vapour performance using an unvented wall example. The CMHC vapour-permeance value for brickwork is about 45 Pa/ng·s·m²; this qualifies it as a Type 2 vapour barrier. Values used in Britain [62, 63] provide a range of from 25 to 100 Pa/ng·s·m² and in Germany they range from as low as 20 to as high as 400 Pa/ng·s·m² (see Section 1.8). Calculating the vapour gradient through a typical wood-frame house wall indicates that condensation can often occur. If moisture penetrates the air/vapour barrier of the poly/drywall assembly, considerable amounts of water may be deposited on the rear of the brick or within the wall itself. However, in a ventilated wall, the vapour pressure in the cavity would be depressed and condensation might be avoided (Figure 5.6).



Note: Vapour pressures in Pascals

Figure 5.6: Effect of Ventilation on Condensation Behind Vapour Resistant Cladding

It is possible to generate a combined vapour resistance of a wall layer which includes the effects of both diffusion and mass flow. The mass of water in air can be found from a form of the ideal gas law (see Section 3.3.2):

$$w_w = \frac{p_v \cdot V}{R_{wv} \cdot T}$$

where w_w is the mass of water (kg),

p_v is the vapour pressure of water (Pa), V is the volume of air (m^3),

R_{wv} is the gas constant for water (461.5 J/kg·K), and

T is the temperature (K).

For a difference in vapour pressure, therefore, assuming well-mixed air, the mass of water transported by an air volume exchange is:

$$\Delta w_w = \frac{\Delta p_w \cdot \Delta V}{R_{wv} \cdot T}$$

The transfer of water vapour through a wall layer is the water-vapour permeance. For an air flow rate of 0.28 litres per second (0.00028 $m^3/s = 1\ m^3/hr$), a vapour pressure difference of 1 Pa, and a mean temperature of 15 °C, the mass of water transferred, or the equivalent permeance due to ventilation only, is:

$$\Delta w_w = \frac{\Delta p_w \cdot \Delta V}{R_{wv} \cdot T}$$

$$\Delta w_w = \frac{1 \cdot 0.00028}{461.5 \cdot (273+15)} \cdot 10^{12}\ \text{ng/kg}$$

$$= 2100\ \text{ng} \cdot \text{s} \cdot \text{m}^2/\text{Pa}.$$

This value of permeance is over forty times that of the CMHC value for a 90 mm brick masonry veneer. This indicates that, at the very least, ventilation can play a very important role in bypassing the vapour resistance of the brick veneer.

To account for the resistance of the brickwork, a parallel circuit analogy can be used, and an equivalent resistance and permeance calculated:

$$\frac{1}{R_{equiv}} = \frac{1}{R_{v,vent}} + \frac{1}{R_{v,screen}} = M_{v,vent} + M_{v,screen}$$

In this case the vapour diffusion resistance of the screen is negligible. Even with a ventilation rate of only 0.1 m^3/hr, the transfer of vapour out of the cavity by mass transport is likely to be from four to five times greater than by diffusion. Table 5.1 lists the equivalent ventilation vapour permeance of a screened wall for various ventilation rates.

Ventilation Flow Rate **l / m²·s**	**Equivalent Vapour Permeance** **ng·s·m² /Pa**
0.05	375
0.10	750
0.25	1 875
0.50	3 750
1.00	7 500
3.00	22 600

Note: By comparison, the vapour permeance of brickwork and wood siding is approx. 50 ng·s·m² /Pa

Table 5.1: Equivalent Vapour Permeance for Various Ventilation Flow Rates

The air velocity in a cavity 2.5 m high and 25 mm deep necessary to generate 2.5 m³/hour of air flow (0.28 lps/m²) is 0.028 m/s. Although this velocity is so slow it is difficult to measure and the pressures necessary to generate the small flow rate are generally considered so small as to be insignificant (i.e. $\Delta P << 1$ Pascal), Table 5.1 confirms that such small rates can have a drastic effect on the actual vapour permeance of the screen.

For most typical screens (vinyl siding, brick cladding, metal cladding, precast concrete), the resistance to vapour diffusion is very high and the satisfactory performance of the wall assemblies can be explained by ventilation, albeit exceedingly small, of the cavity. If drainage of the condensation were the only available mechanism of removing moisture, the backside of the cladding would need to be so wet that sufficient liquid water were present to drain – a potentially damaging situation.

5.4 Assessing Ventilation Drying

The equivalent ventilation permeance can easily be substituted for the permeance of brick veneer in a standard Glaser vapour flow analysis. From such analysis it can be shown that a relatively small ventilation rate (e.g., less than 0.25 lps) will greatly reduce the chance of condensation on the backside of a brick veneer.

A Glaser analysis can also be undertaken which accounts, on a very simple level, for air leakage and ventilation by calculating an equivalent permeance for the air barrier (i.e. assuming a leakage rate). If the air barrier leakage is high or concentrated at one location, the air flow will change the temperature profile of the wall assembly to such an extent that the analysis would not be even approximately correct.

By making the drying assumptions described in section 5.2 (i.e., the cavity sides are saturated and the drying rate is controlled by the ventilation rate), and using the concept of equivalent permeance developed above, the maximum ventilation drying rate can be calculated for various cavity and exterior weather conditions. It is a rather simple task to generate drying potential curves given the monthly average exterior conditions.

Figure 5.7 presents the results of calculations based on ventilation permeance and using average weather data for Waterloo, Ont. (i.e., the vapour pressure of exterior air and the vapour pressure within a saturated cavity) for four months of the year. For example, given a ventilation flow rate of only 0.1 lps, a drying rate of up to 10 g/day can be achieved in January and about 100 g/day in July. Flow rates of 0.5 to 1 lps could likely be achieved in practice with proper ventilated wall design and construction (see Figure 4.3). Figure 5.7 indicates that ventilation rates of this magnitude can remove moisture, even in the winter.

Figure 5.8 provides a flow chart for assessing ventilation effectiveness on a more individual and accurate basis than the charts and graphs presented thus far in this report.

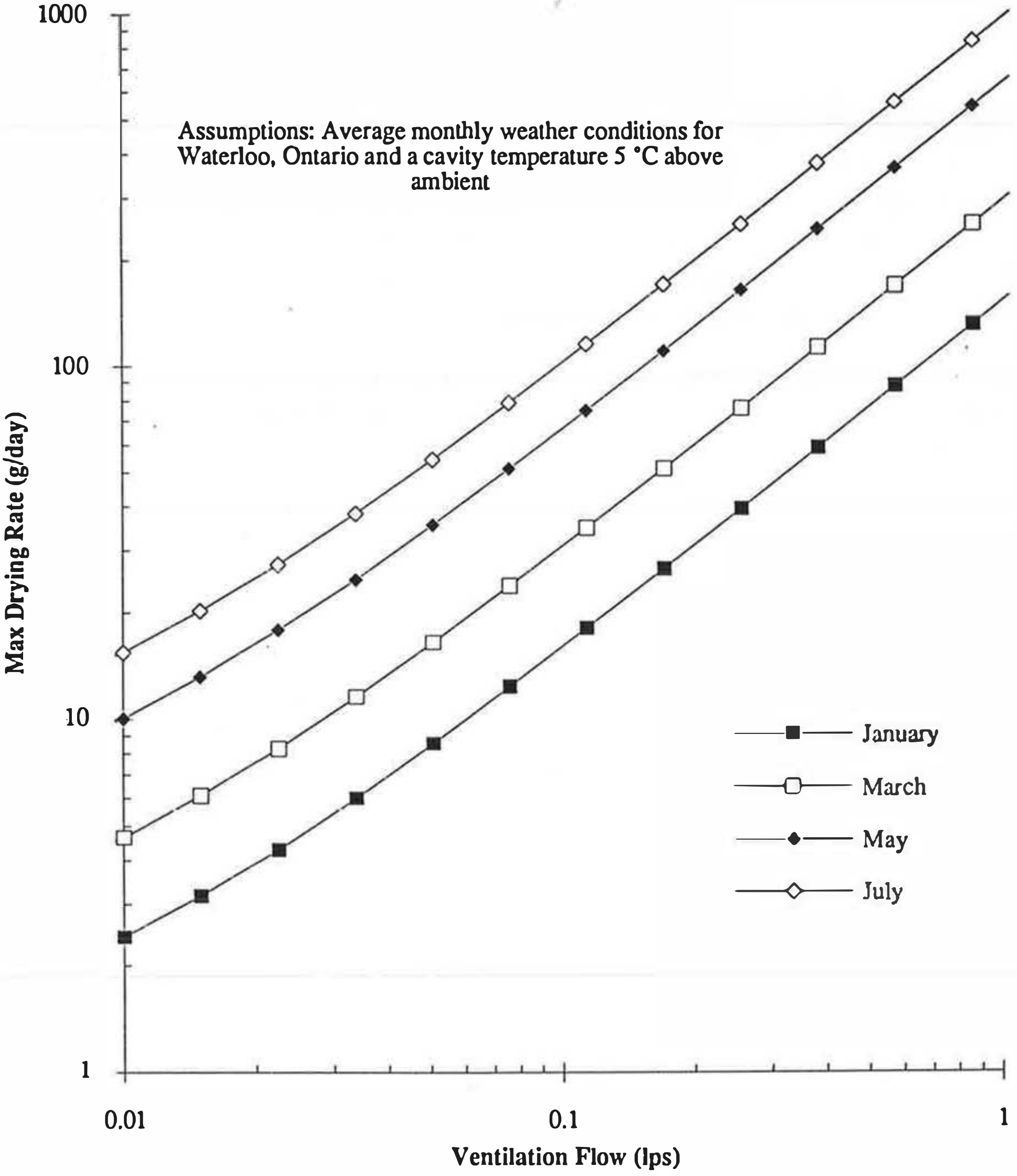


Figure 5.7: Ventilation Drying Potential versus Ventilation Flow for Waterloo, Ont.

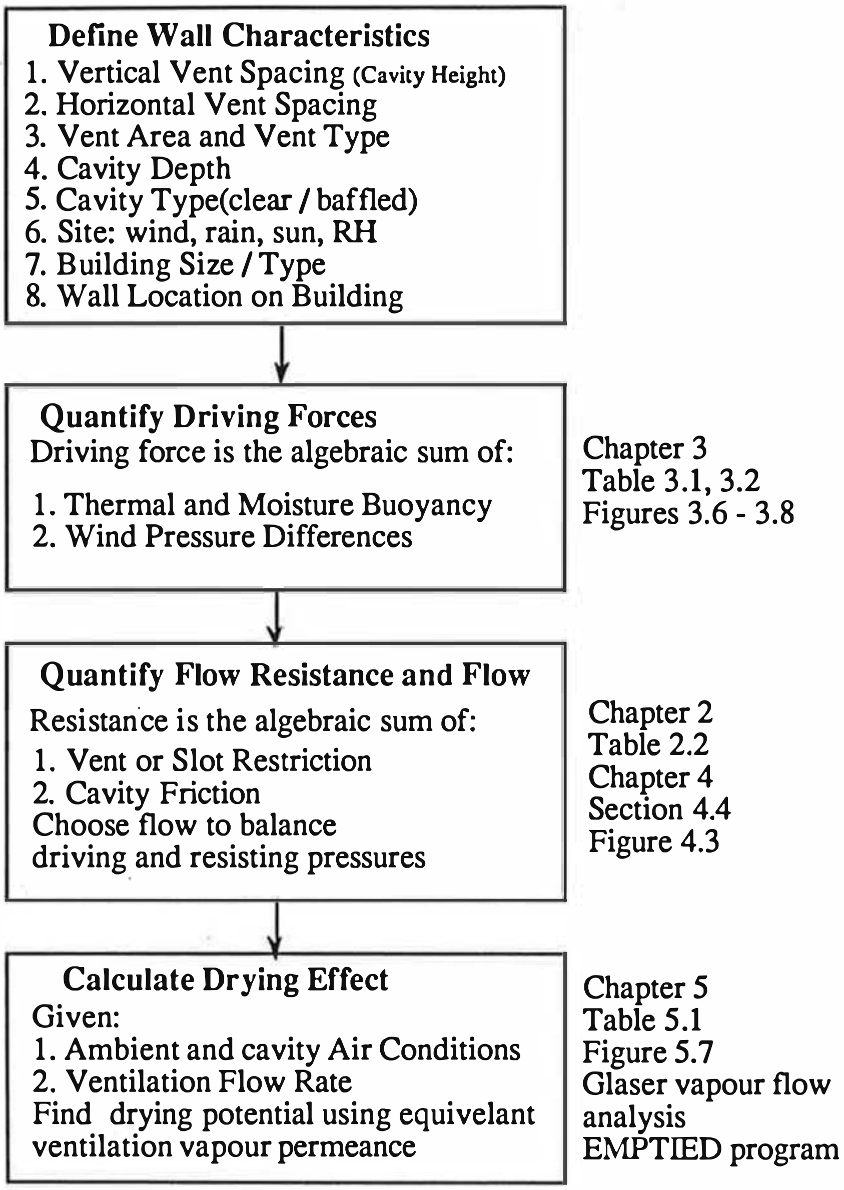


Figure 5.8: Ventilation Assessment Procedure

5.5 Controlling Ventilation Wetting

Only the drying potential has explicitly been examined in this report. There are, however, cases where ventilation may cause wetting. For ventilation to be of benefit, its drying potential must be significantly higher than its wetting potential.

For thermally lightweight cladding with well ventilated cavities (metal cladding systems are especially vulnerable) and roofs, night time condensation can cause wetting. Maximum and minimum venting areas for these systems must be carefully chosen.

For most wall systems, the cladding is warmer than the outdoor air (because of solar heating, thermal mass, and in winter, outward heat flow) and the possibility and duration of condensation within the cavity is small. This danger exists only if radiation losses reduce the temperature of the cladding below ambient. For brick veneer systems, the possibility of night time condensation on the inner face can be practically ruled out.

If the cavity is faced on the inside with a highly vapour and air-permeable insulation (i.e., all mineral fibre insulations without some facing), condensation on the underlying sheathing may occur in air-conditioned buildings. This is unlikely to be a problem for most wall assemblies because the summertime temperature difference between outdoor and indoor air rarely exceeds 10°C and a barrier to air and water flow is often located outside some insulation. In fact, most significant vapour flow reversals are due to solar-driven evaporation of water from porous screens, and ventilation can greatly assist in reducing the vapour pressure in the cavity and removing moisture, thus reducing the potential for condensation.

Because significant inward-acting summertime vapour drives occur in all veneer walls and excessive wind and convective cooling will occur in low-density fibrous insulated sheathing, a facing should be provided on the exterior (cavity) face of these products. Such a facing will greatly reduce the probability of summertime condensation induced by ventilation and inward diffusion, as well as reducing convective heat loss.

The addition of vent openings increases the chance of wind driven rain penetrating into the cavity. While it is felt that the amount of water penetration through most vents is small or negligible, this question deserves further research.

6. Conclusions and Recommendations

6.1 Conclusions

Ventilation, even small amounts, can provide significant benefits to wall performance, mostly by removing moisture from behind the screen. If unobstructed cavities and several large vents are provided in a screened wall, significant ventilation air flow can occur, even with the very small driving pressures that typically occur in service. The same measures will allow for the moderation of wind-induced pressure differences across the screen.

Ventilation is primarily driven by a combination of wind pressures, thermal buoyancy and moisture buoyancy. The provision of vent openings at the top and bottom of the cavity will generally allow the most ventilation. Pressures driving ventilation can be expected to be in the order of 1 Pascal. The flow generated by these pressures will be in the order of 0.1 to 1.0 litre per second per m^2. These flows can remove from 10 to 1000 g/m^2/day of moisture from behind the screen, depending on the exterior environment. Designing or retro-fitting wall systems for ventilation can greatly increase the amount of ventilation drying.

Full-scale testing has shown that for steady or slowly-varying air-flow calculations, standard (10 x 65 x 90 deep) open head joints in masonry veneers can be considered to behave as orifices with a flow coefficient of 0.65 and a flow exponent of 0.55. Other orifices closely follow the power law. Flow through orifices is higher under large amplitude dynamic pressures than under static pressures but the actual flow is difficult to predict with standard orifice flow equations.

All of the commercially available masonry veneer vent inserts tested under static and dynamic pressures greatly restricted flow. The flow through these inserts ranged from 1 to 15% of the flow through an open head joint.

6.2 Recommendations For Construction

Ventilation should be encouraged in all screened walls, but especially in walls with screens and inner wythes that can absorb moisture (masonry, wood, etc.). Increased venting is also one of the simplest and most effective means of increasing the degree of pressure moderation.

In masonry veneer construction, it is recommended that minimum venting, i.e., an open head joint every 600 mm o.c. *at the top and bottom* of a 2.5 m high cavity or 0.2% of the wall area, should be provided. To achieve significant benefits from pressure moderation and ventilation drying, at least three times this area (0.6% of area of wall) should be provided. Leaving a protected continuous open bed joint at the top of the cavity instead of open head joints will increase ventilation flow by 30 to 45% and increase the degree of pressure moderation.

Presently available commercial masonry veneer vent inserts greatly reduce air flow, and their use should therefore be avoided if ventilation drying and pressure moderation are desired. It is recommended that some effort be expended to develop an effective vent insert.

To ensure clear cavities (which encourage good ventilation and allow drainage), the minimum width of the air space should be 30 mm, preferably a width of 40-50 mm should be provided.

In locations with climates that have large wetting potentials, the use of open jointed, well-drained and ventilated panel systems should be seriously considered for exterior wall systems.

6.3 Recommendations For Further Research

Additional laboratory and field exposure research should be conducted to verify theoretical and laboratory experimental predictions of the drying potential of ventilation.

The identification and quantification of the most significant wetting (rain, condensation) and drying (drainage, diffusion/evaporation, ventilation) mechanisms in typical brick veneer walls under service conditions are sorely needed.

The effect of orientation and climate on ventilation potential needs to be studied in greater depth. The spatio-temporal pressures acting on building envelopes are very important to both pressure moderation and ventilation.

The mechanism of ventilation within walls with small vent areas (especially vinyl siding) requires further research.

Minimum levels of venting should be considered for inclusion in codes after the appropriate research and demonstration have been conducted.

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Appendix A

Assessing Ventilation Drying: A Design Example

A design example is presented here to indicate how the information presented in this report can be used to predict the potential ventilation drying in buildings.

The example building is a 10-storey, brick-veneer clad apartment building with the dimensions shown in Figure A.1, located in Waterloo, Ontario. Following the ventilation assessment procedure presented earlier in Figure 5.8, the following data are listed:

A. Define Wall Characteristics

1. Vertical Vent Spacing: 2.5 m
2. Horizontal Vent Spacing: 600 mm
3. Every head joint left open in the top and bottom courses
4. Cavity Depth: 50 mm
5. Cavity Type: partially baffled by mortar
6. Site: Waterloo, Ontario, South-facing wall
7. Building Size : 25 m high, 75 m long, 20 m deep
8. The upper corner (i.e., those that get wettest from rain and stack-effect-driven exfiltration).

B. Quantify Driving Forces

1. Thermal Effects

The brickwork in an insulated brick veneer wall will, because of retained solar energy, remain at least 5 °C above ambient over all seasons. From interpolation of Table 3.1, Figure 3.2 or the equation $\Delta P = 3465 \cdot \Delta h \left(\frac{1}{\Delta T_{out}} - \frac{1}{T_{cav}}\right)$ the long-term average pressure driving flow can be estimated as about 0.5 Pascals.

2. Wind Effects

From Atmospheric Services data, the average hourly wind speed from the west-south-west to the east-south-east ranges from just under 3 m/s to about 4.5 m/s at the reference height of 10 m above grade. To adjust the velocity to the top of the building, the velocity should be adjusted as:

$$V_{25} = (25,10)^{0.1} \cdot V_{10}$$

$$= 1.1 \cdot 2.9 = 3.2 \text{ m/s (winds from south east)}$$

$$= 1.1 \cdot 4.5 = 4.9 \text{ m/s (winds from south-west)}$$

This range of mean wind speeds translates to a stagnation pressure of $0.647 \cdot V^2$ or 6.7 to 15.5 Pascals.

From Figure 3.9, the ventilation gradients scaled from the building would be about 0.1, from the bottom to top of the cavity and perhaps 0.2 horizontally. These values would hold over a wide range of wind directions. Therefore, ventilation pressures due to the wind would be between about 0.7 to 1.5 Pascals over the cavity height of 2.5 m and 1.5 to 3.0 Pascals between patio doors onto balconies (say 6 m).

Dynamic variations of the wind speed and temperatures means that the magnitude and direction would vary enormously, but the average values above suggest that an average vertical ventilation pressure of 1 to 2 Pascals could be expected to be realistic.

C. Quantify Flow Resistance and Flow

The flow resistance for a system with similar vents at the top and bottom of the cavity can be found from

$$\Delta P_{drive} = 2\cdot\Delta P_{vent} + \Delta P_{cavity} = 2\cdot\left(\frac{Q}{0.62\cdot A_{vent}}\right)^2 + \frac{Q\cdot h}{4610\cdot\gamma\cdot b\cdot d^3}$$

or, for this example, using a moderately blocked cavity, γ=0.5,

$$\Delta P_{drive} = 2\cdot\left(\frac{Q}{0.62\cdot 0.01\cdot 0.066}\right)^2 + \frac{Q\cdot 2.5}{4610\cdot 0.5\cdot 0.6\cdot .05^3}$$

For a flow rate of 3×10^{-4} m^3/s (0.3 lps), the flow resistance would be 1.0 Pascals. At a flow rate of 4.1×10^{-4} m^3/s (0.41 lps) the flow resistance would be 2.0 Pascals. Therefore, the flow would be between 0.3 and 0.4 lps per 0.6 m width of wall, or about 0.2 or 0.3 lps/m^2.

D. Quantify Drying Effect

From Table 5.1 it is clear that the predicted flow rates would decrease the effective vapour resistance of the brickwork by a factor of 30 to 40. This reduction in vapour permeance of the brickwork will greatly assist the drying of the inner wythe if wetted from rain penetration, condensation, etc.

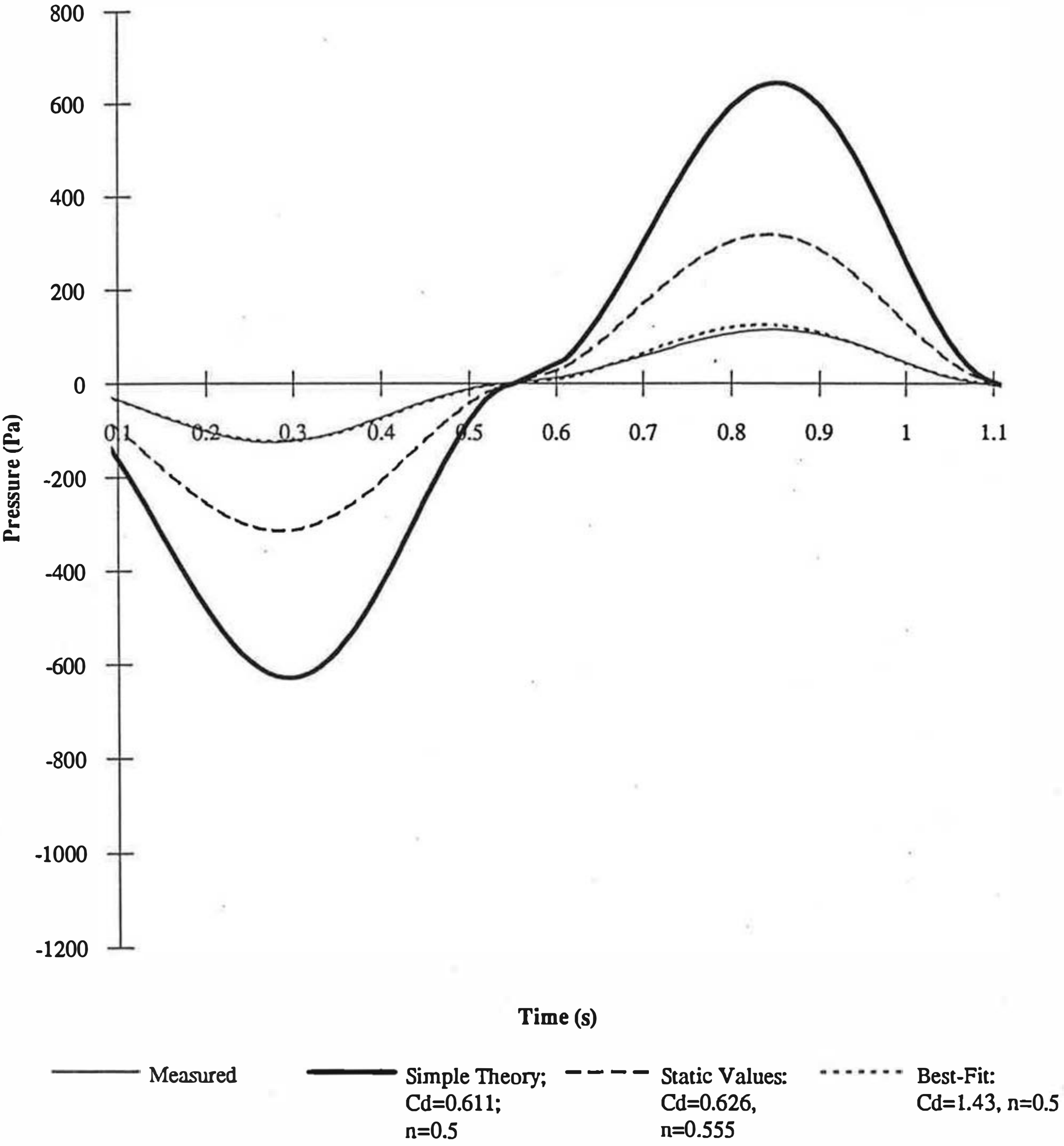
Figure 5.7 suggests that for Waterloo conditions, a flow rate of 0.2 lps/m^2 would result in a drying potential of 100 to 150 g/m^2/day in May (i.e. a period of spring rains) and as much as 200 g/m^2/day in July. While these drying rates may not appear to be very high, they would be beneficial since they are based on long-term average values.

If higher rates of drying are deemed necessary to maintain the brick or inner wythe moisture at lower values, every head joint in the bottom course could be left open. This would triple the ventilation flow rate to 0.6 to 0.9 lps/m^2 and quadruple the May drying rate to 400 to 600 g/m^2/day and ensure a potential drying rate of at least 100 g/day even in January.

Appendix B

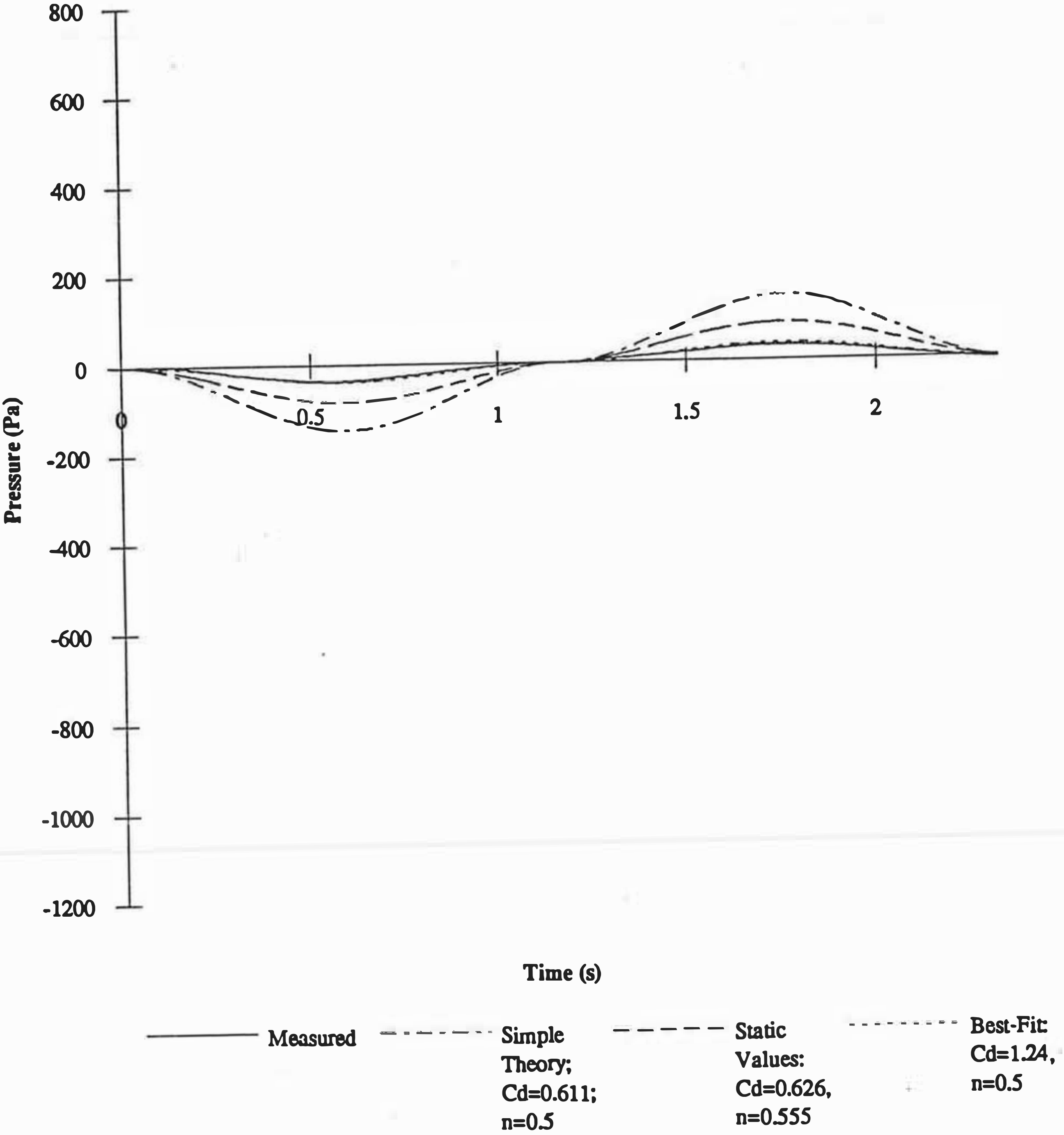
Selected Static and Dynamic Pressure Vent Test Results

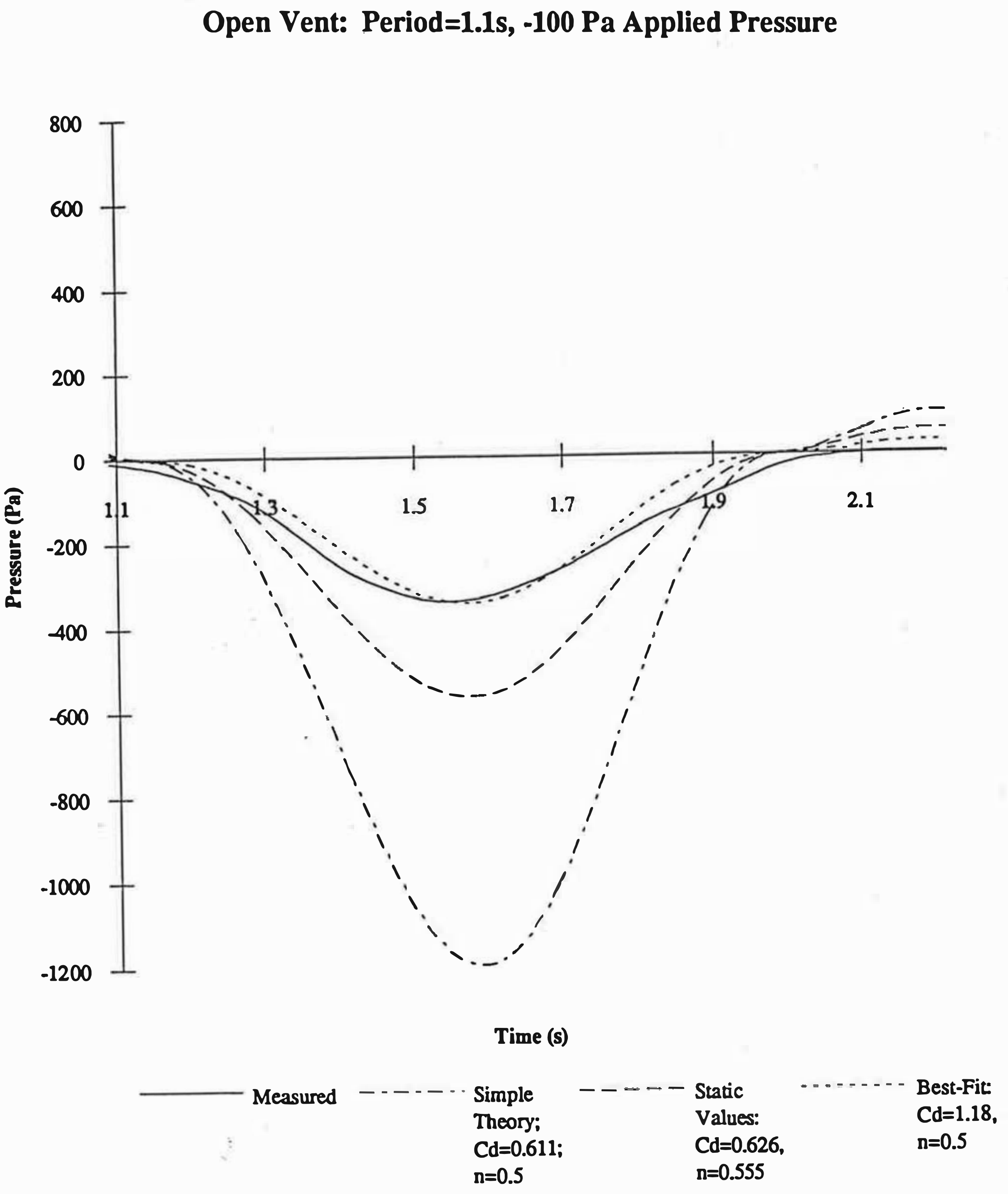
Open Vent: Period=1.1s, No Applied Pressure



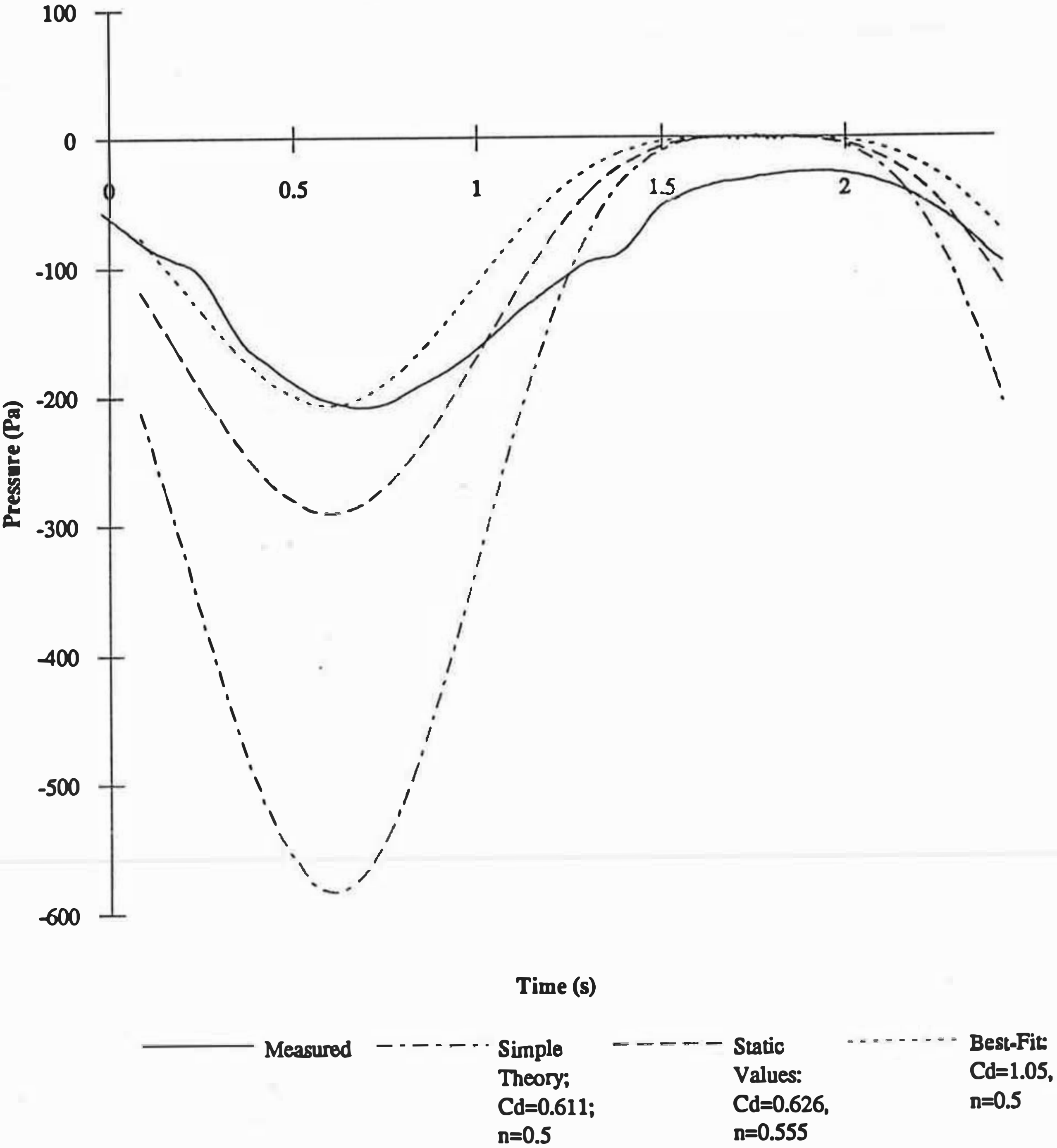
DYNO0_2A.XLC

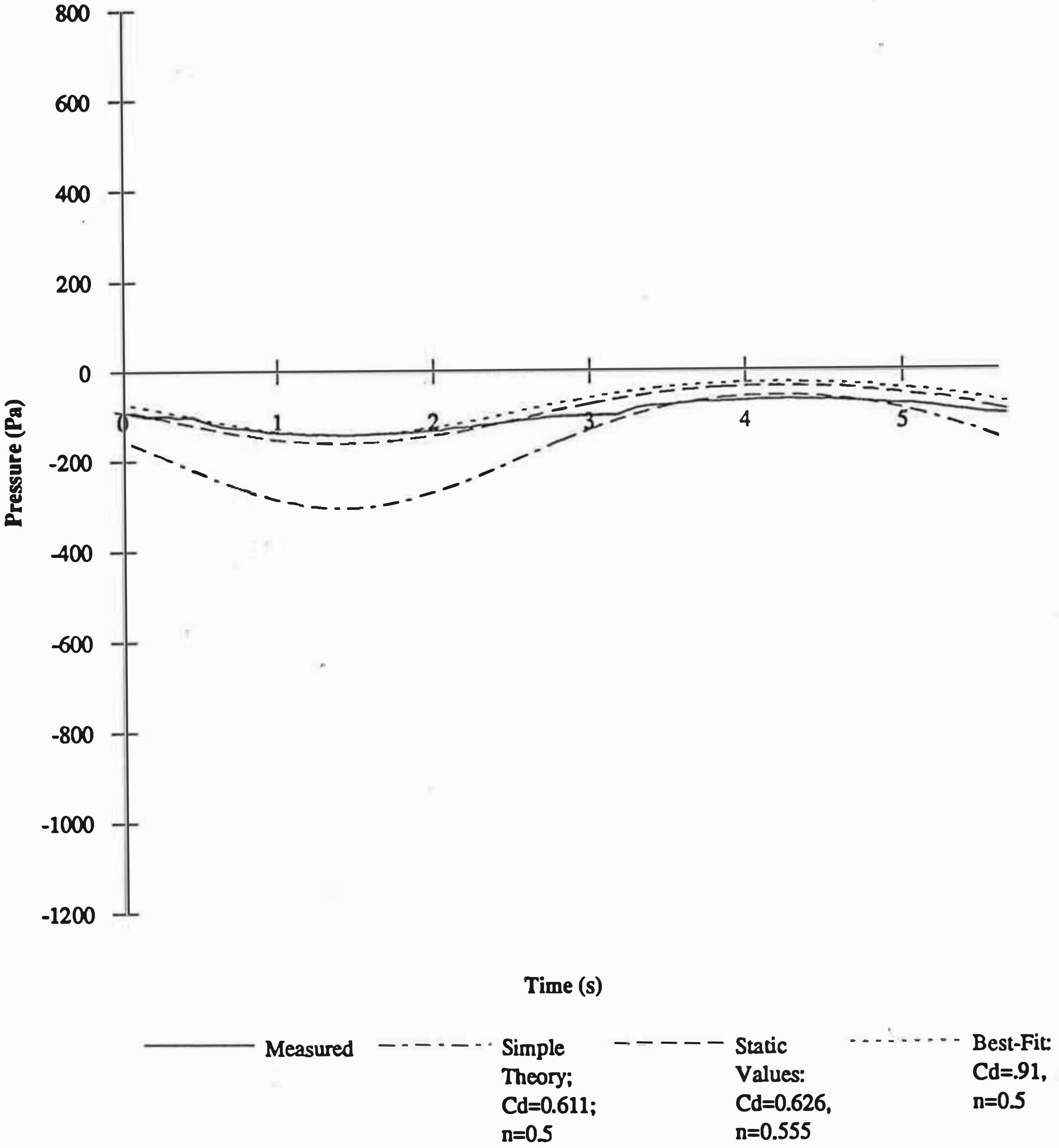
Open Vent: Period=2.3s, No Applied Pressure



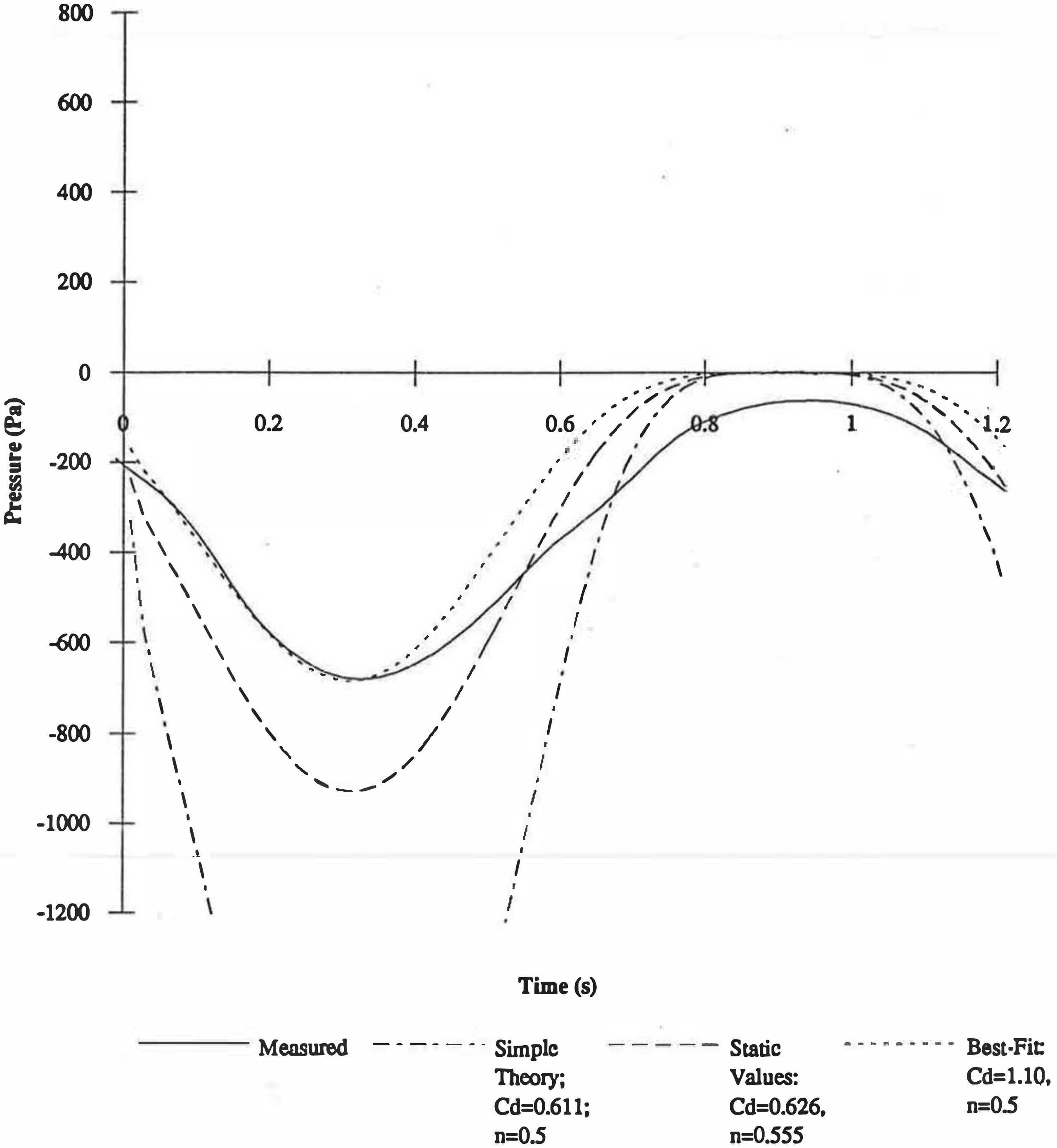

Open Vent: Period=1.1s, -100 Pa Applied Pressure
800
600
400
200
0
-200
-400
-600
-800
-1000
-1200
Pressure (Pa)
1.1
1.3
1.5
1.7
1.9
2.1
Time (s)
Measured
Simple Theory; Cd=0.611; n=0.5
Static Values: Cd=0.626, n=0.555
Best-Fit: Cd=1.18, n=0.5

Open Vent: Period=2.4s, -100 Pa Applied Pressure

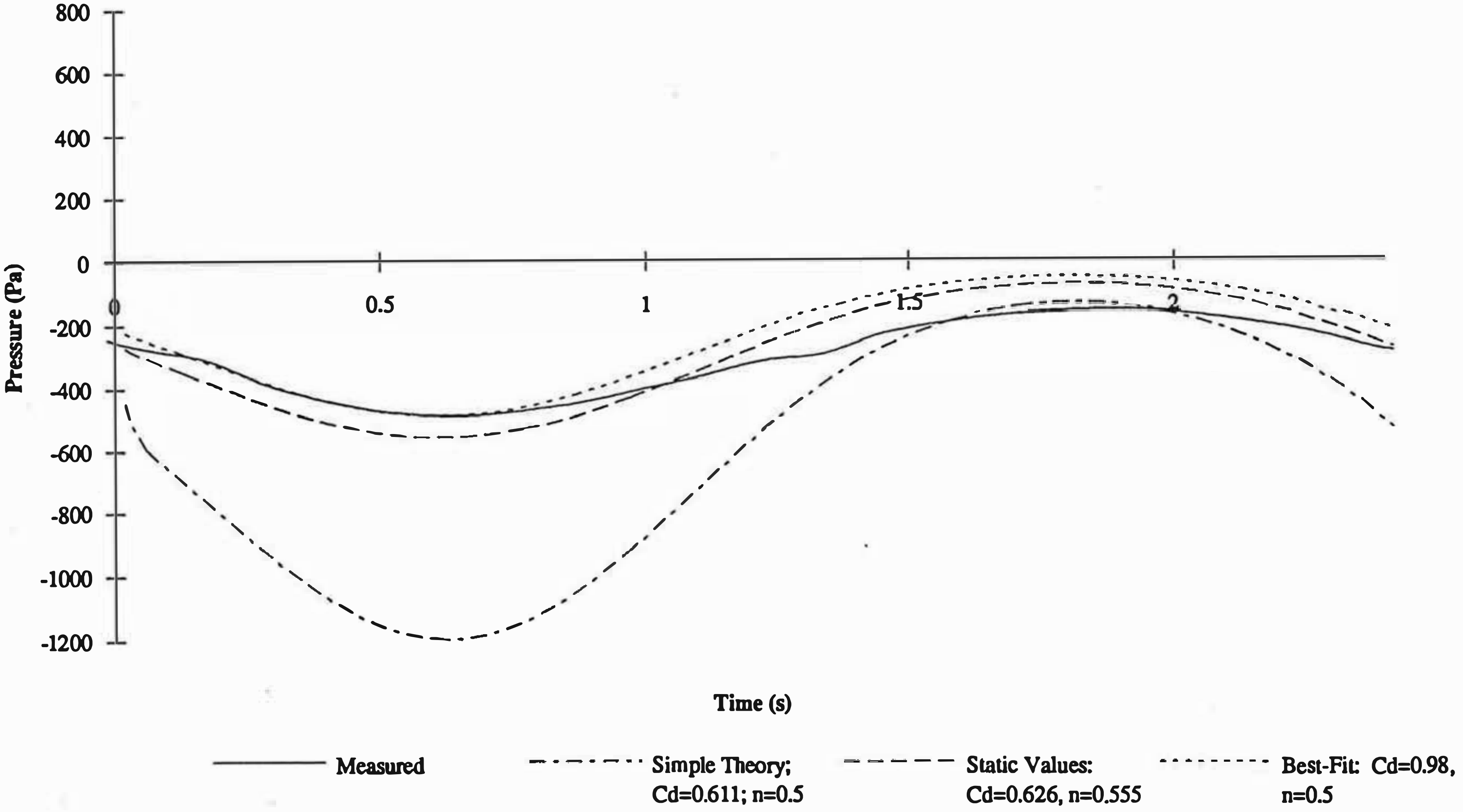




Open Vent: Period=5.6s, -100 Pa Applied Pressure

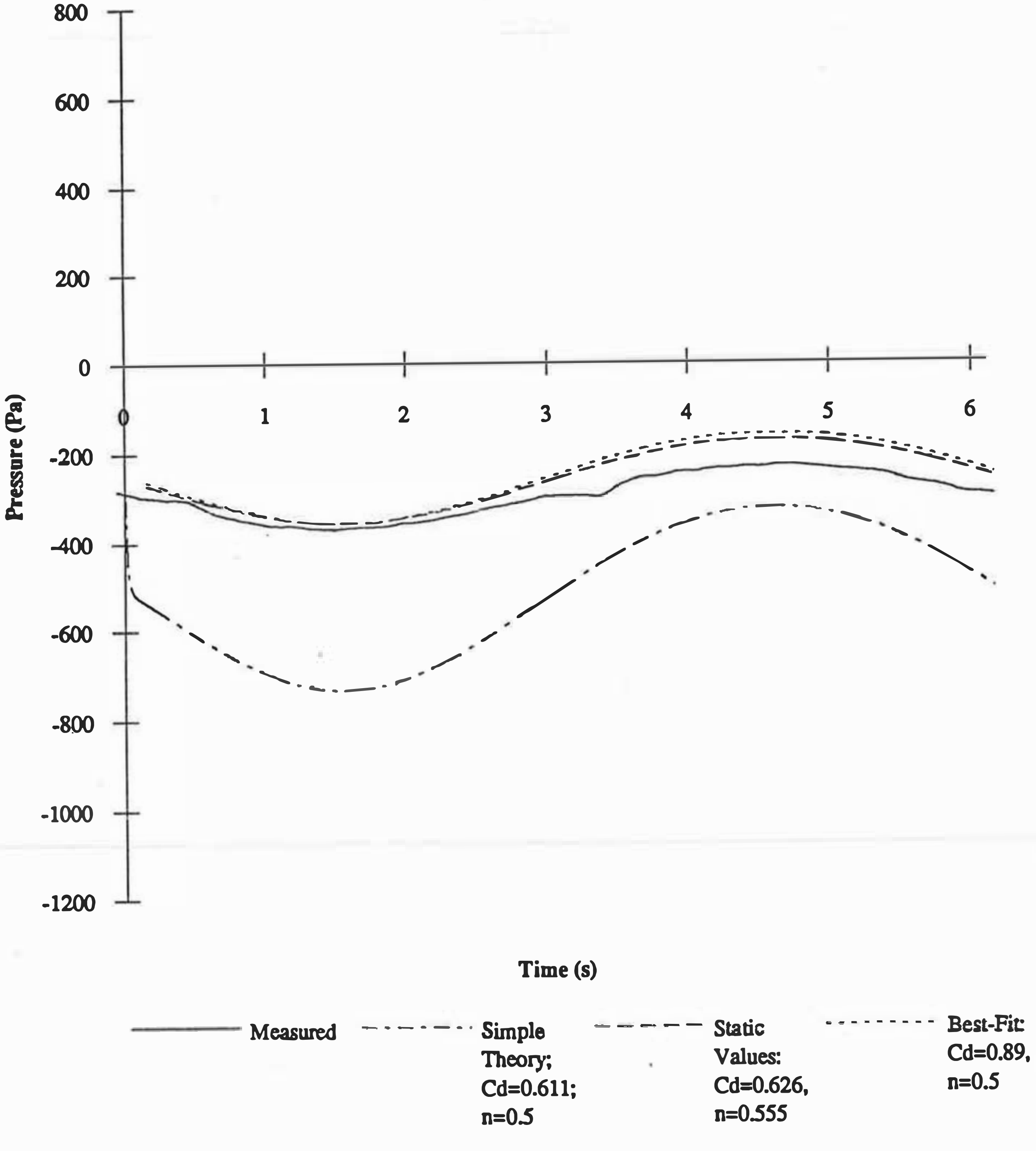


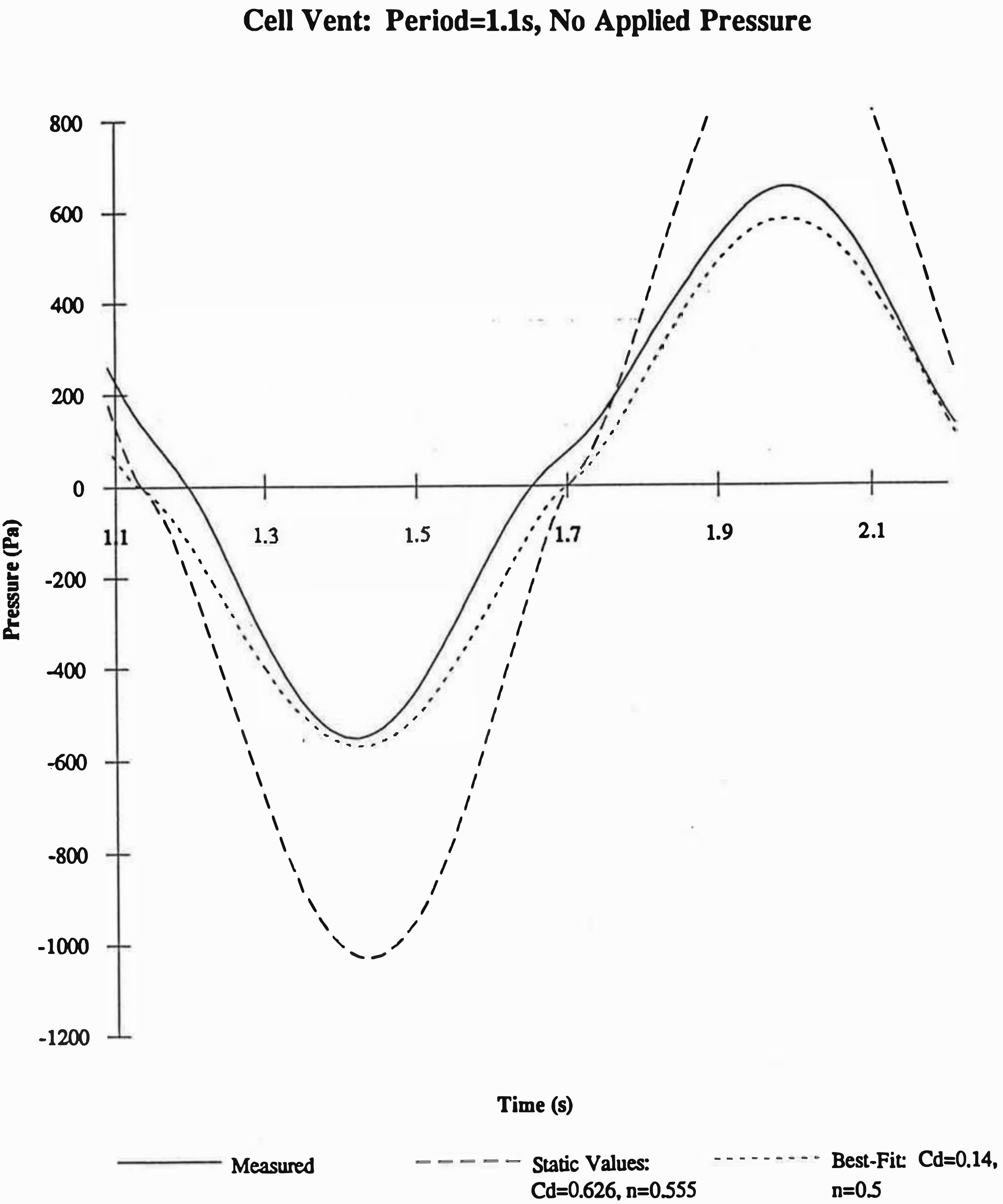
Open Vent: Period=1.2s, -300 Pa Applied Pressure



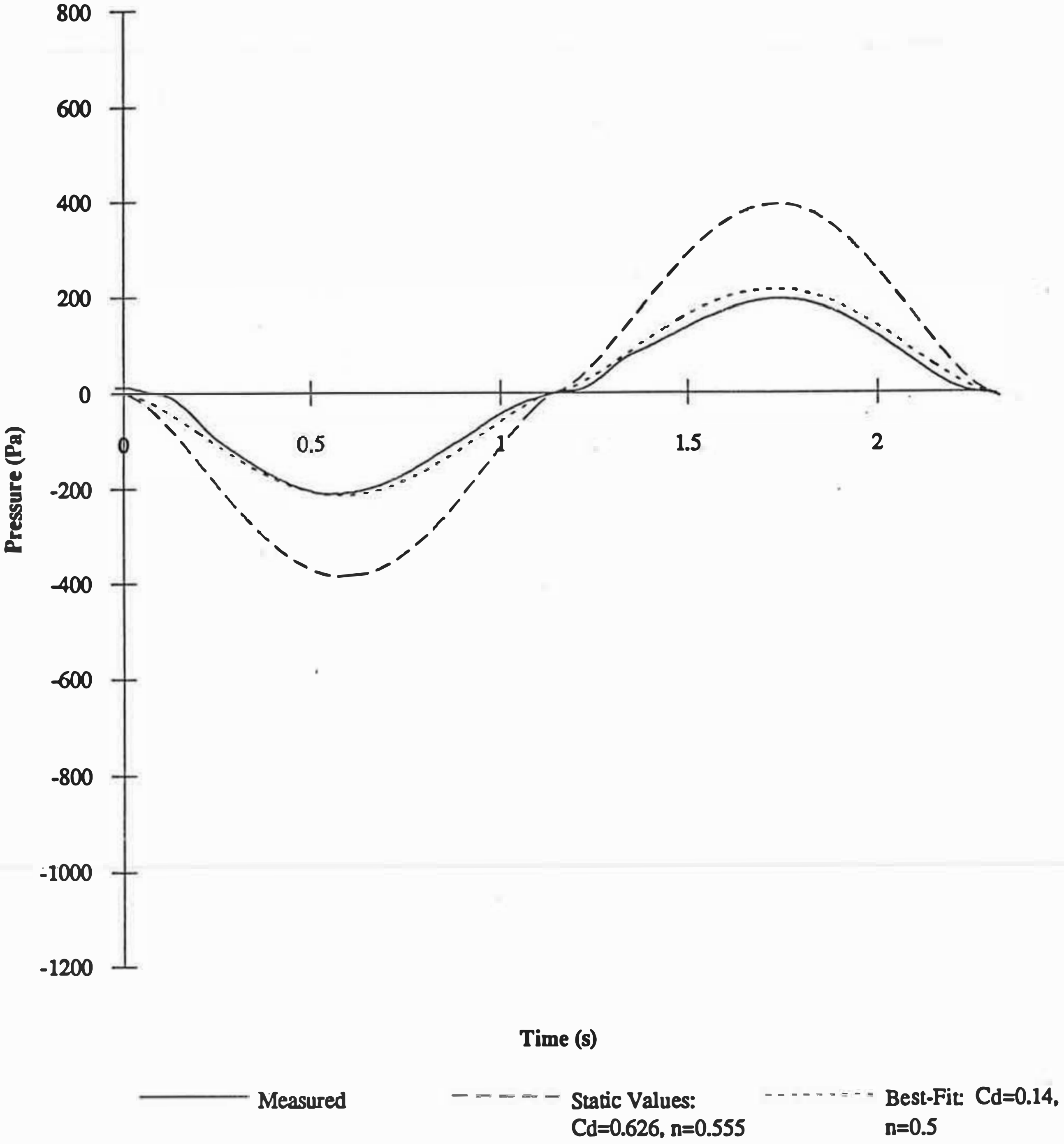
Open Vent: Period=2.4s, -300 Pa Applied Pressure

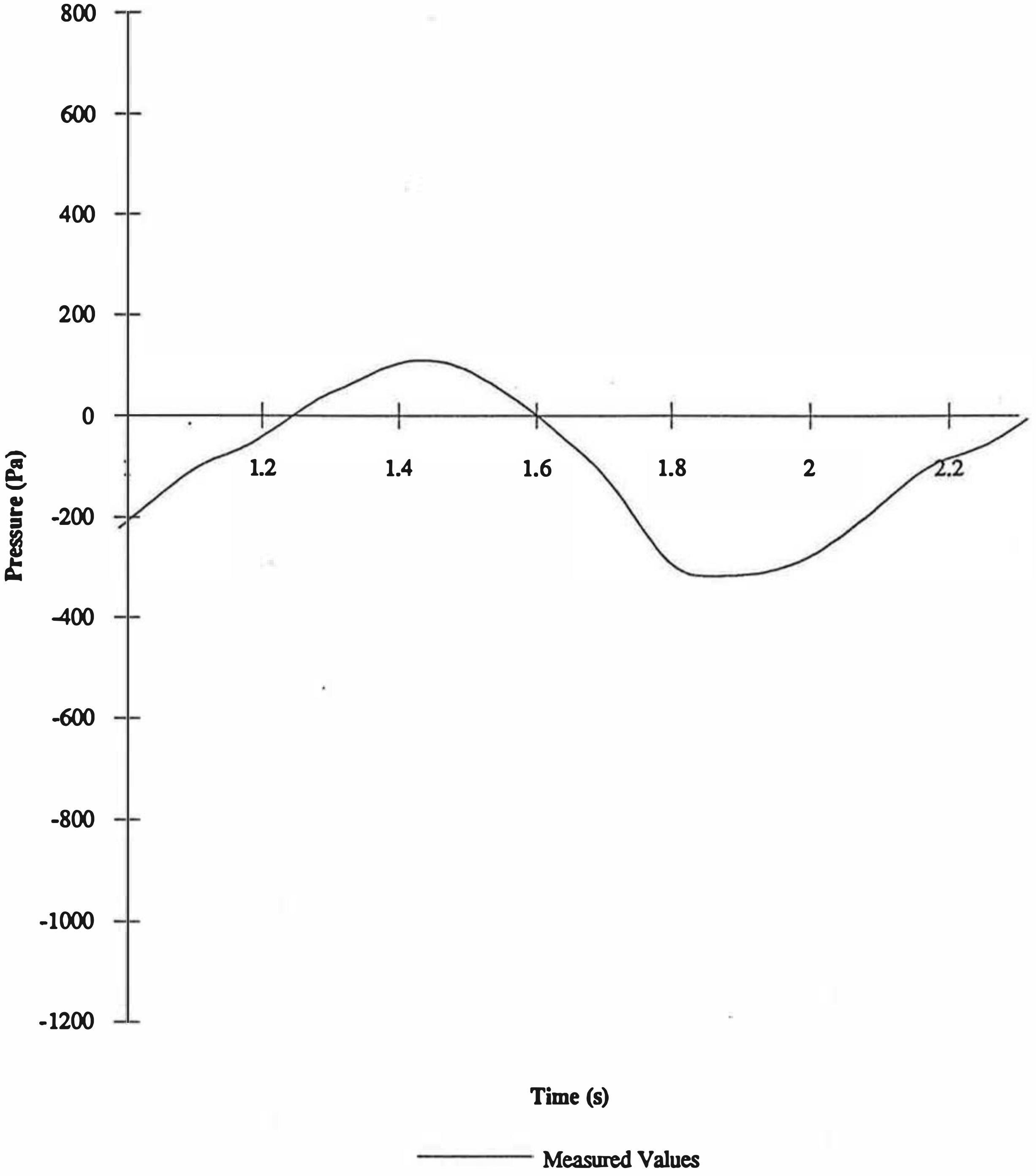
Open Vent: Period=6.1s, -300 Pa Applied Pressure



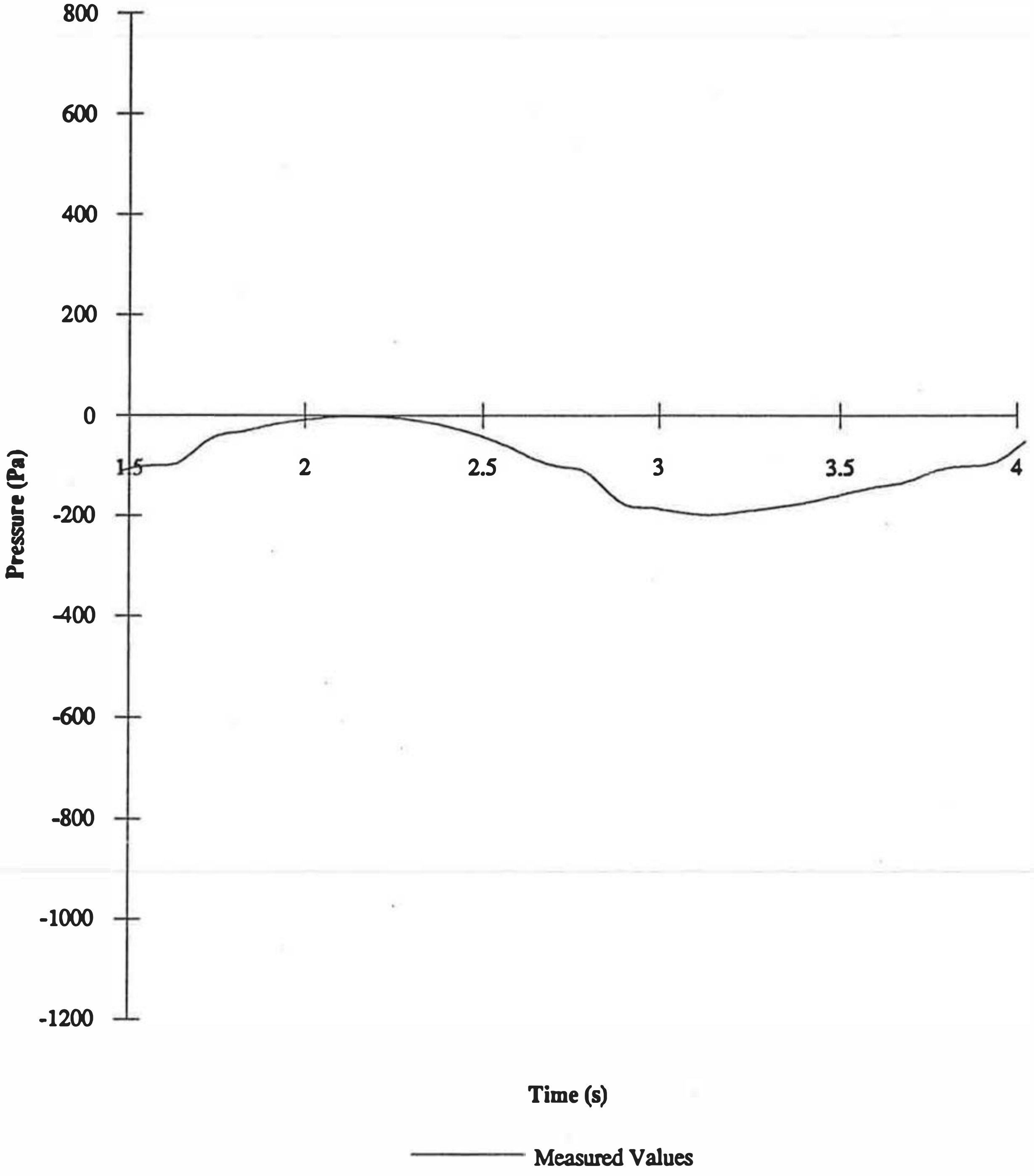

Cell Vent: Period=1.1s, No Applied Pressure
800
600
400
200
0
-200
-400
-600
-800
-1000
-1200
Pressure (Pa)
1.1
1.3
1.5
1.7
1.9
2.1
Time (s)
Measured
Static Values: Cd=0.626, n=0.555
Best-Fit: Cd=0.14, n=0.5

Cell Vent: Period=2.3s, No Applied Pressure



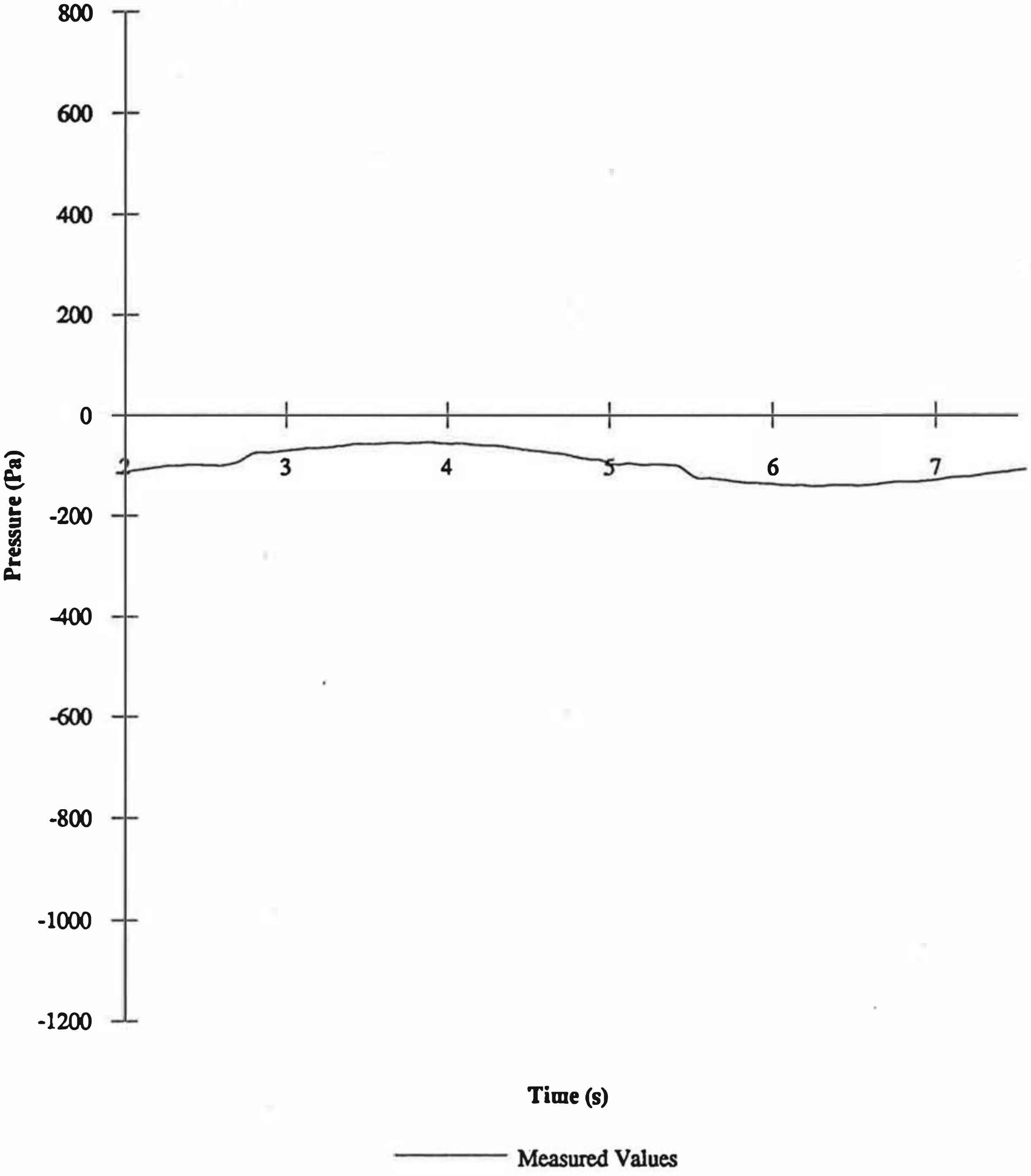


Cell-Vent: Period=1.1s, -100 Pa Applied Pressure

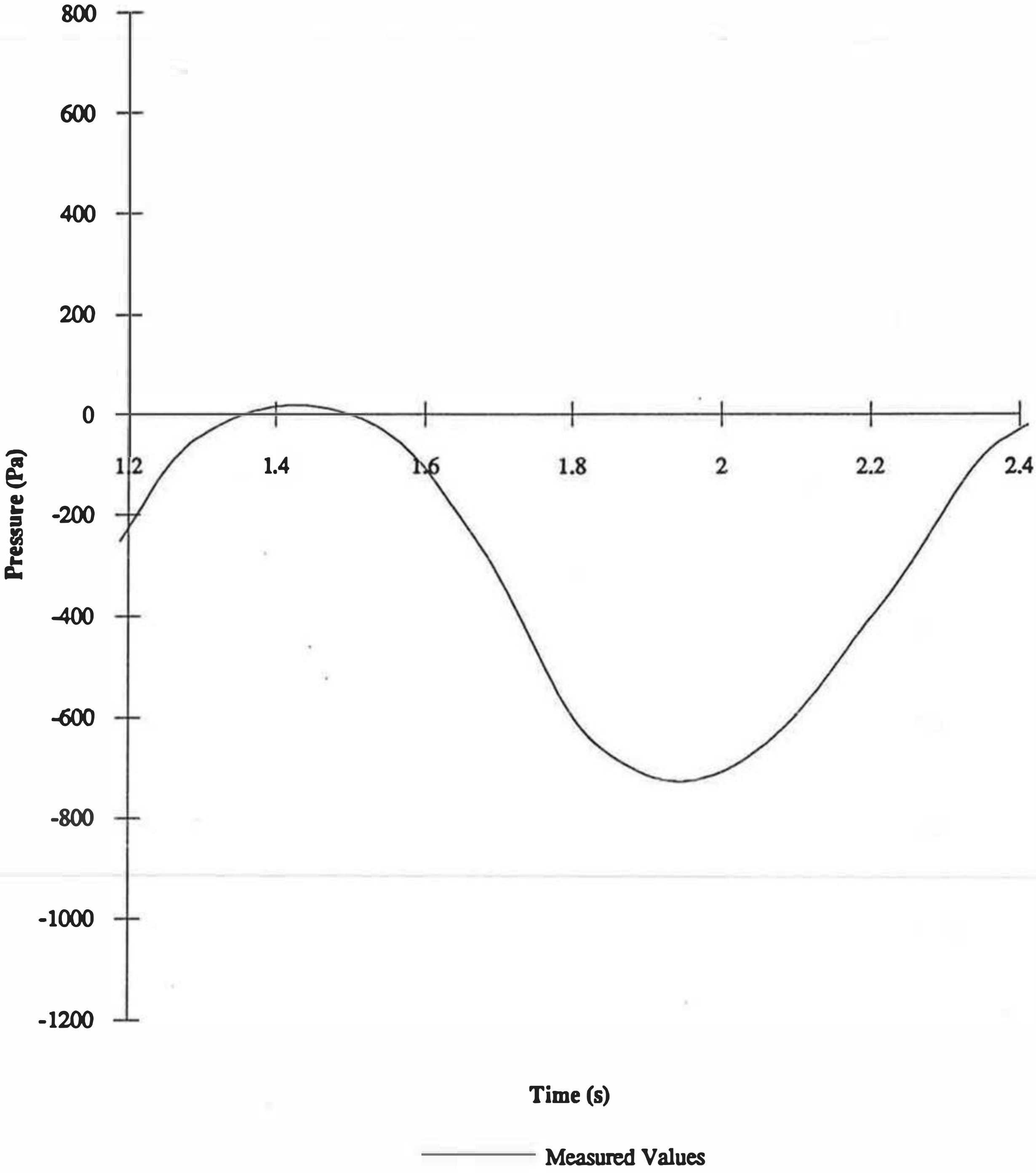


Cell-Vent: Period=2.4s, -100 Pa Applied Pressure

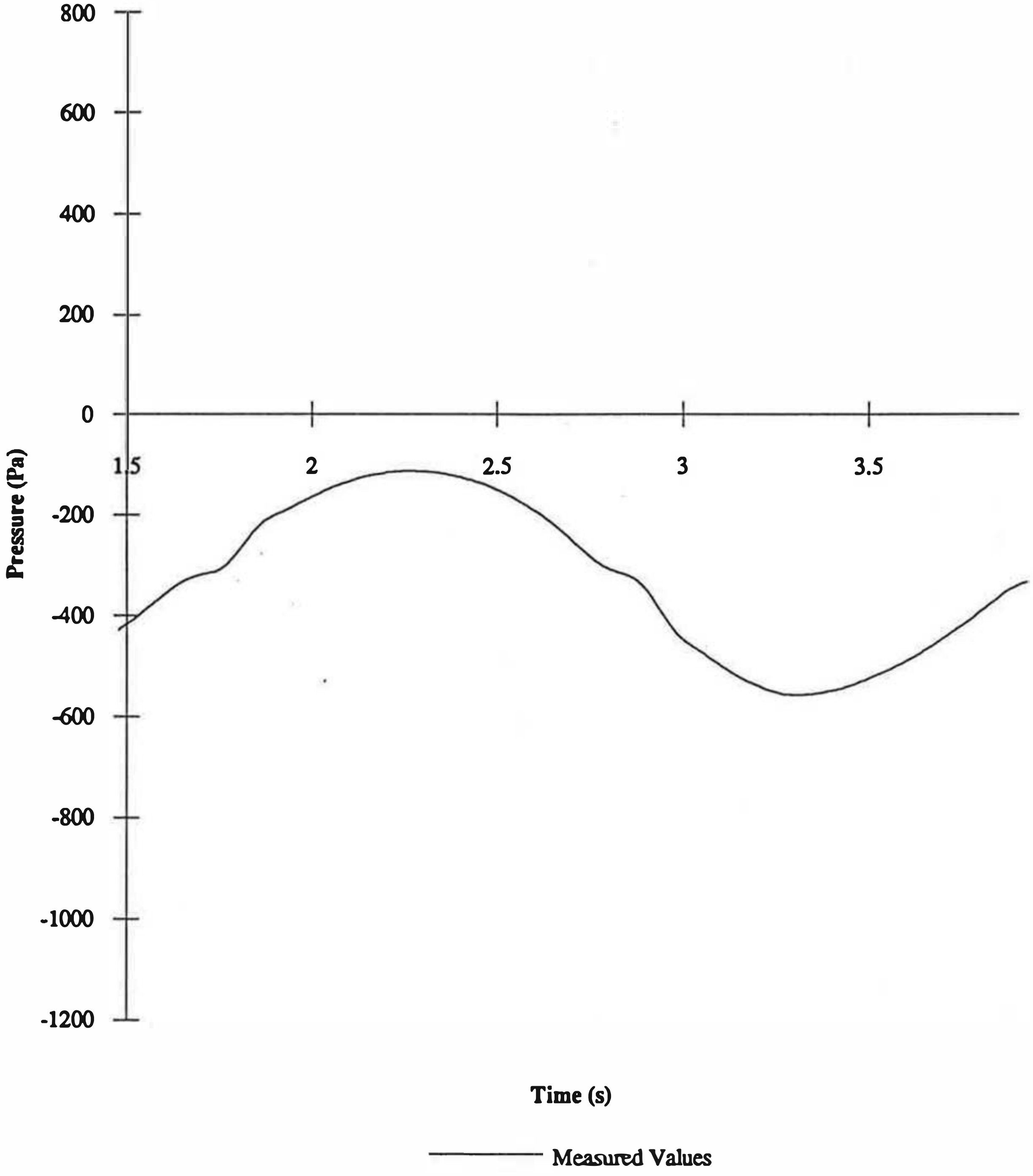
Cell-Vent: Period=5.2s, -100 Pa Applied Pressure



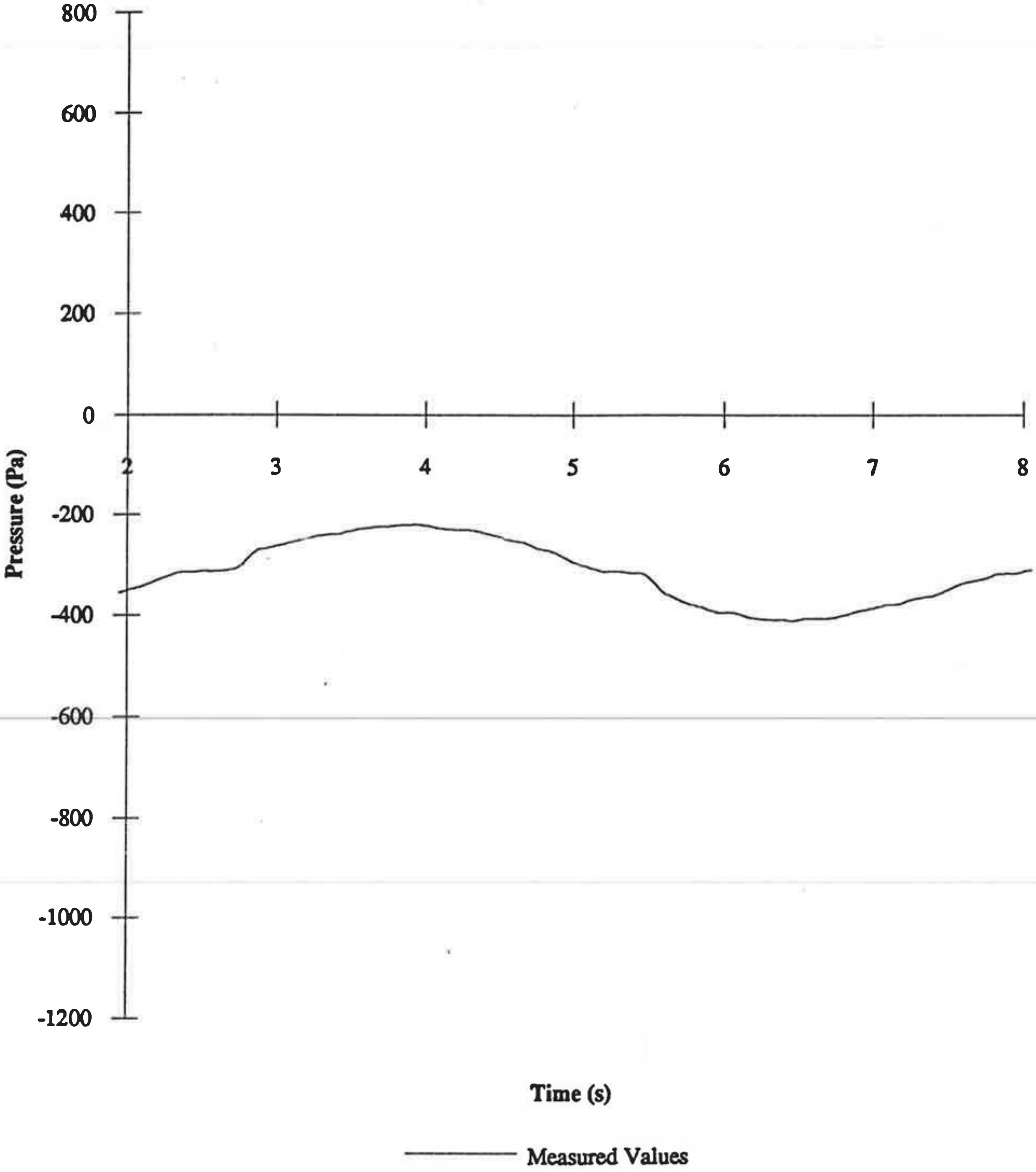
Cell-Vent: Period=1.2s, -309 Pa Applied Pressure



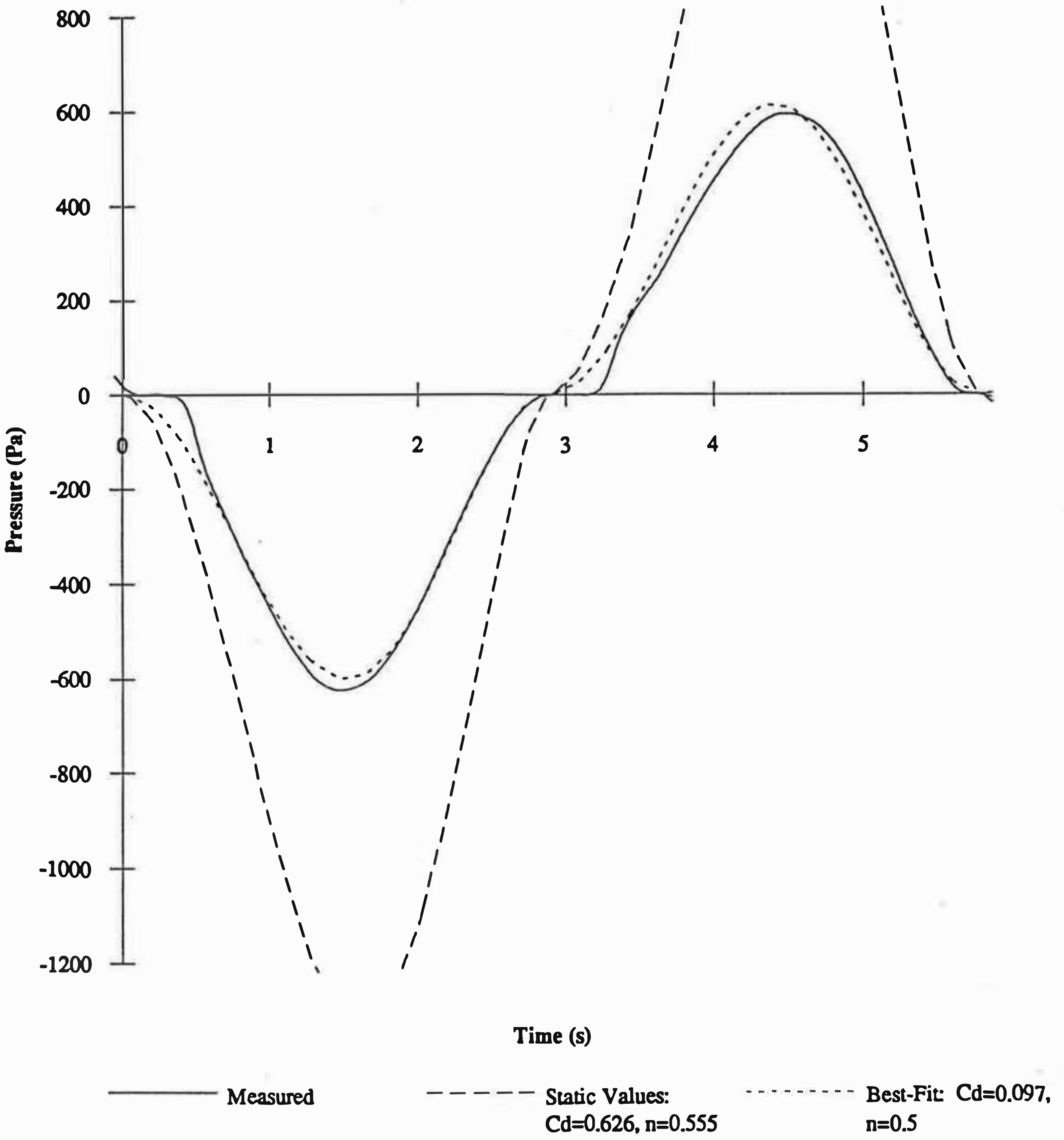
Cell-Vent: Period=2.3s, -319 Pa Applied Pressure



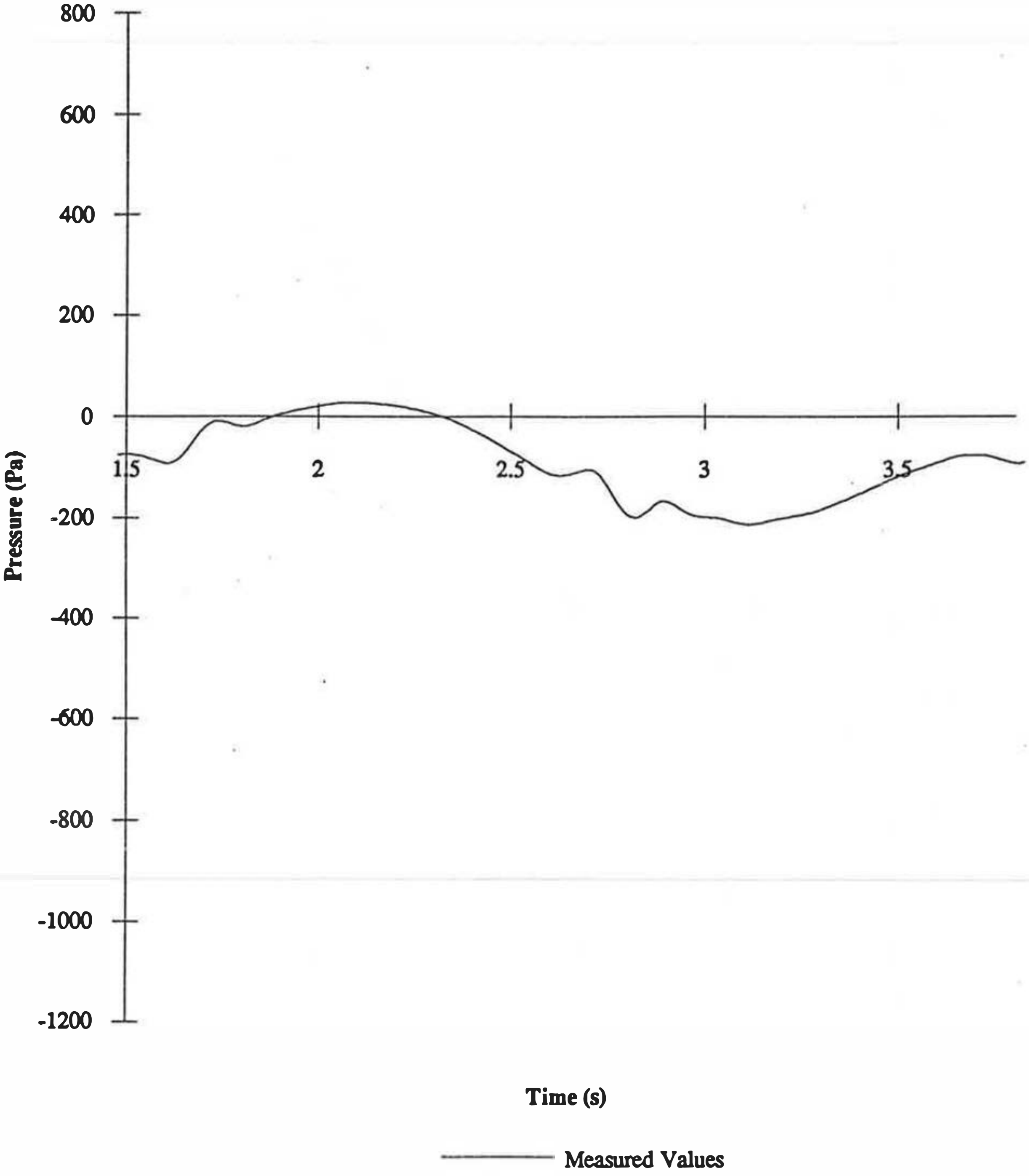
Cell-Vent: Period=5.7s, -315 Pa Applied Pressure



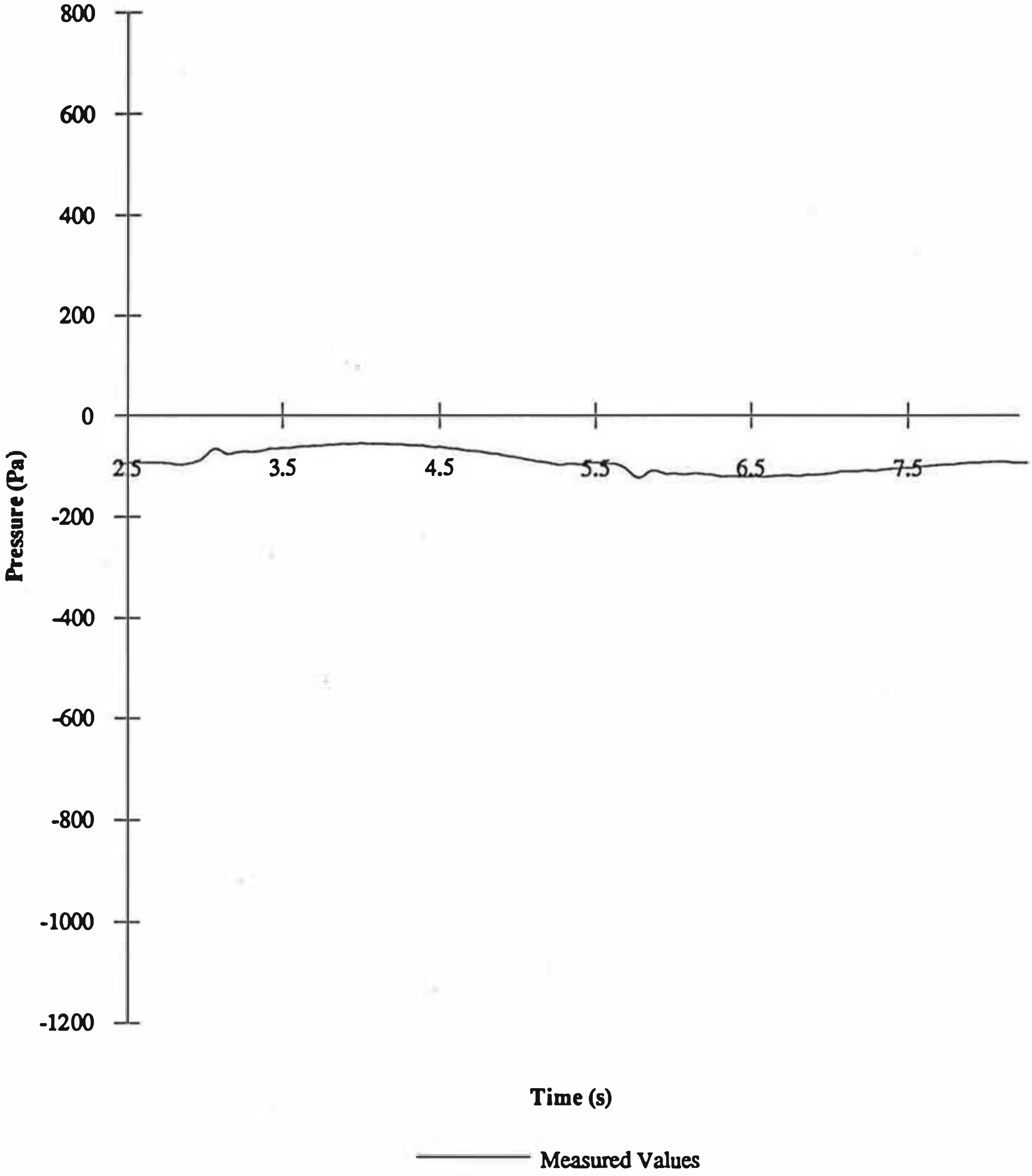
Goodco: Period=5.8s, No Applied Pressure



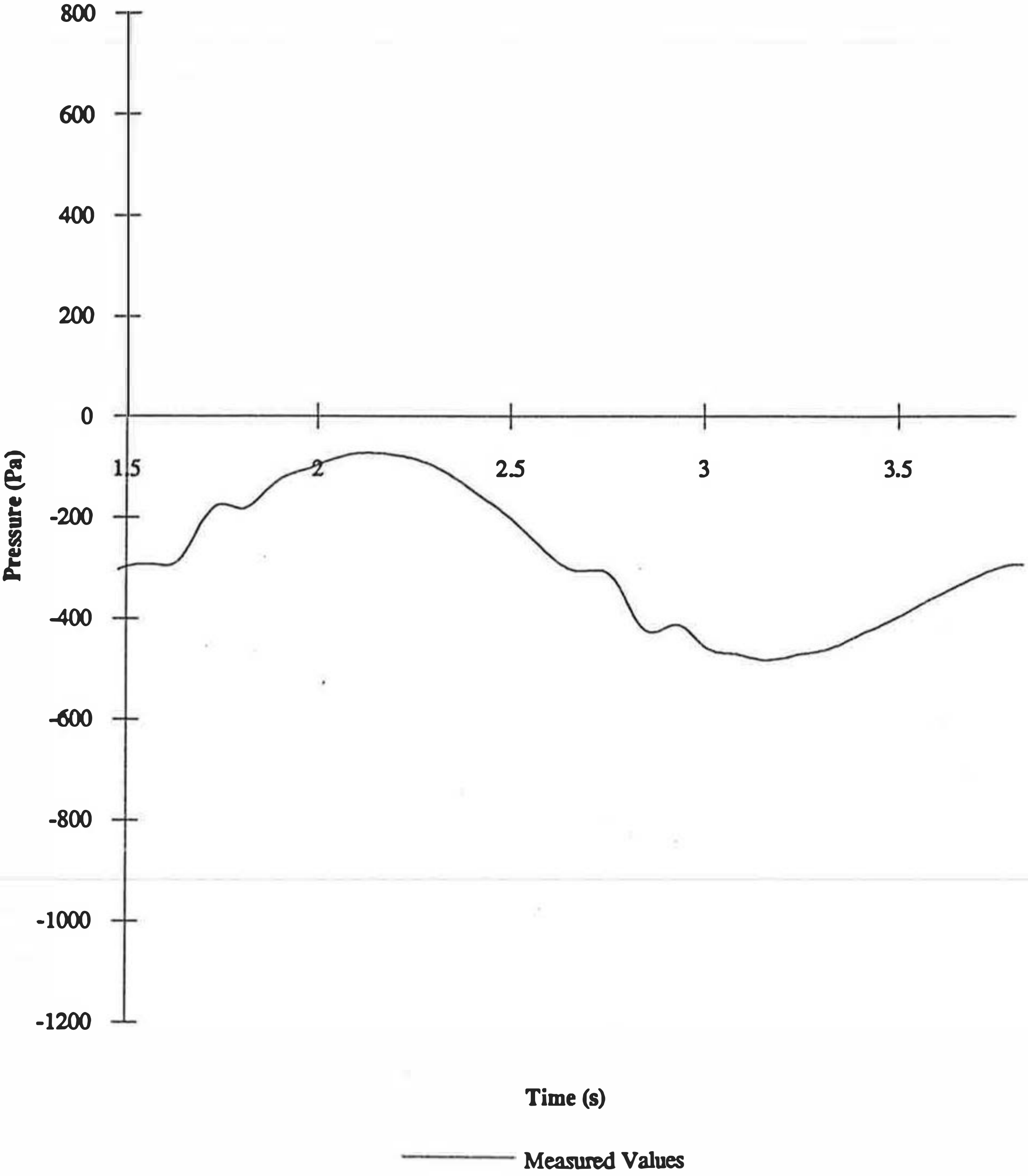
Goodco Vent: Period=2.3s, -97 Pa Applied Pressure



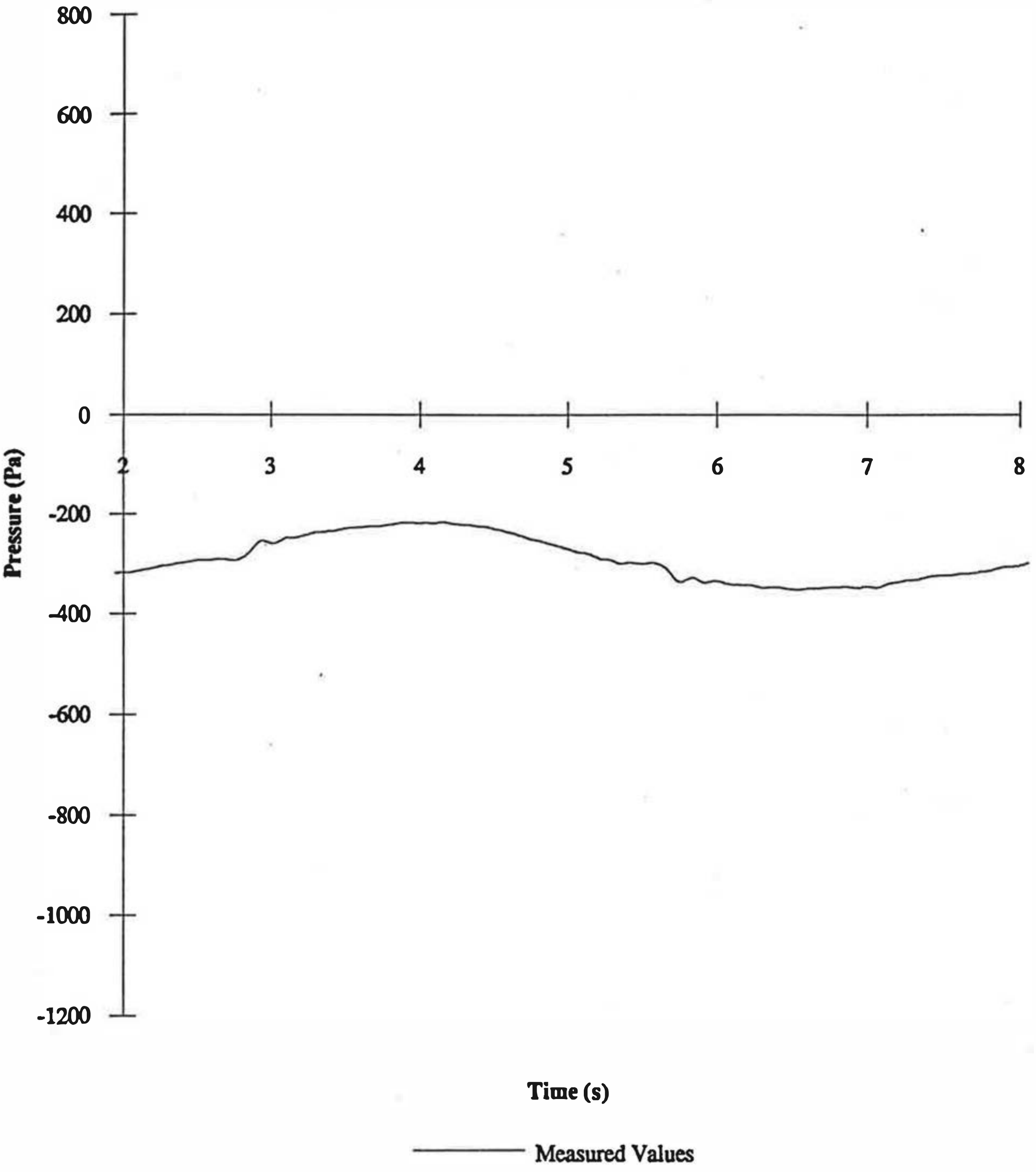
Goodco Vent: Period=5.7s, -94 Pa Applied Pressure



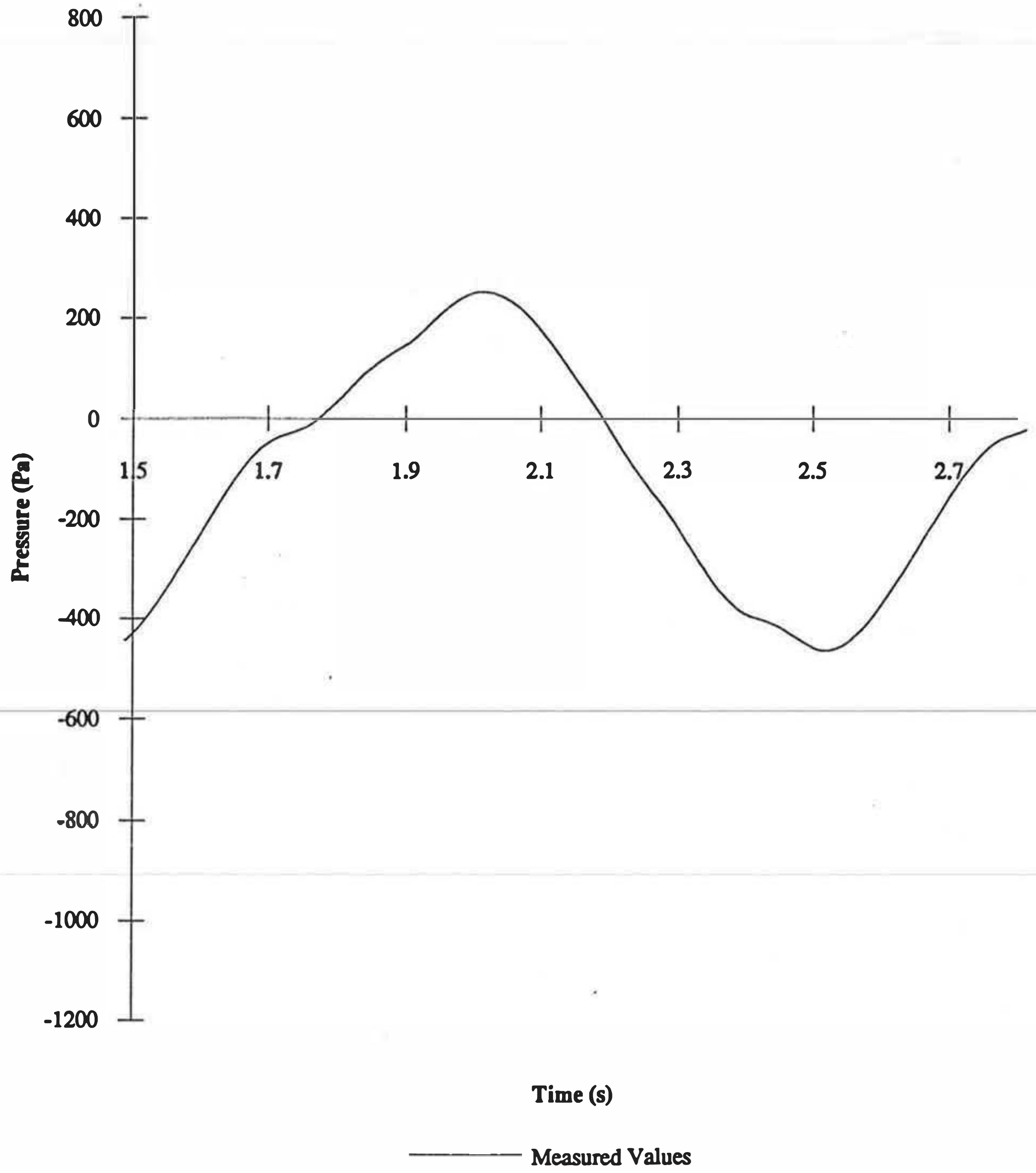
Goodco Vent: Period=2.3s, -303 Pa Applied Pressure



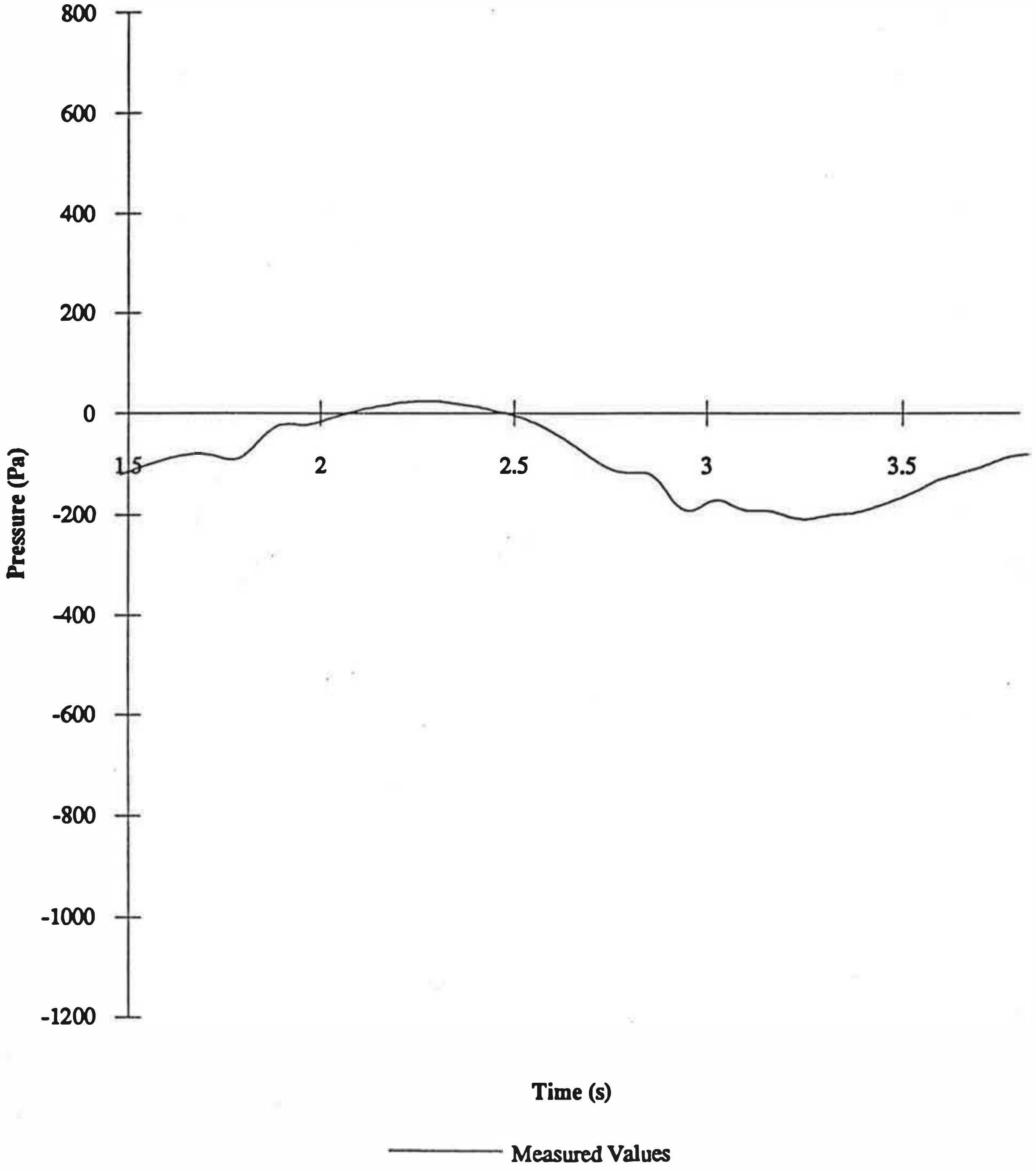
Goodco Vent: Period=5.9s, -293 Pa Applied Pressure



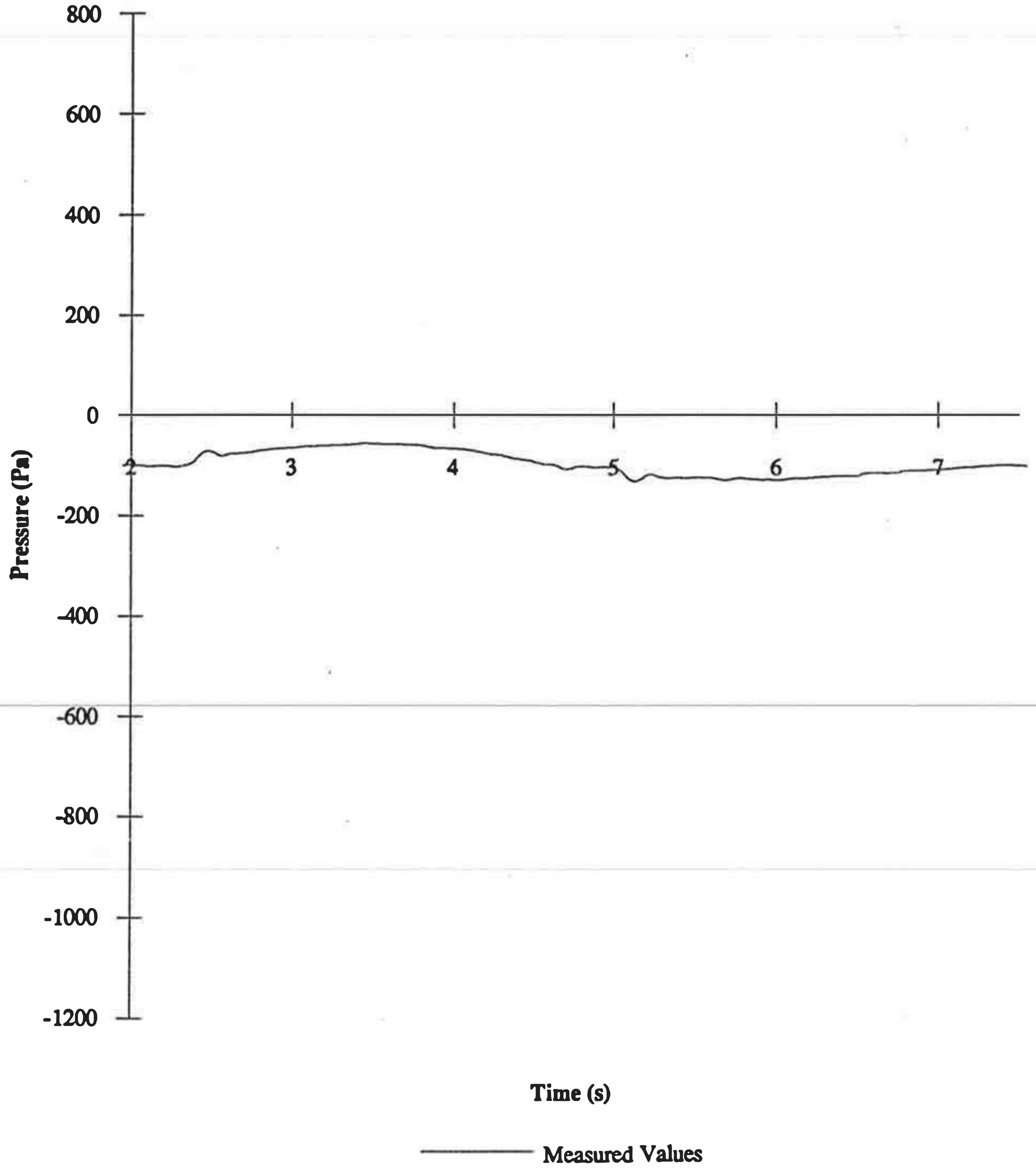
Yeovil Vent: Period=1.1s, -100 Pa Applied Pressure



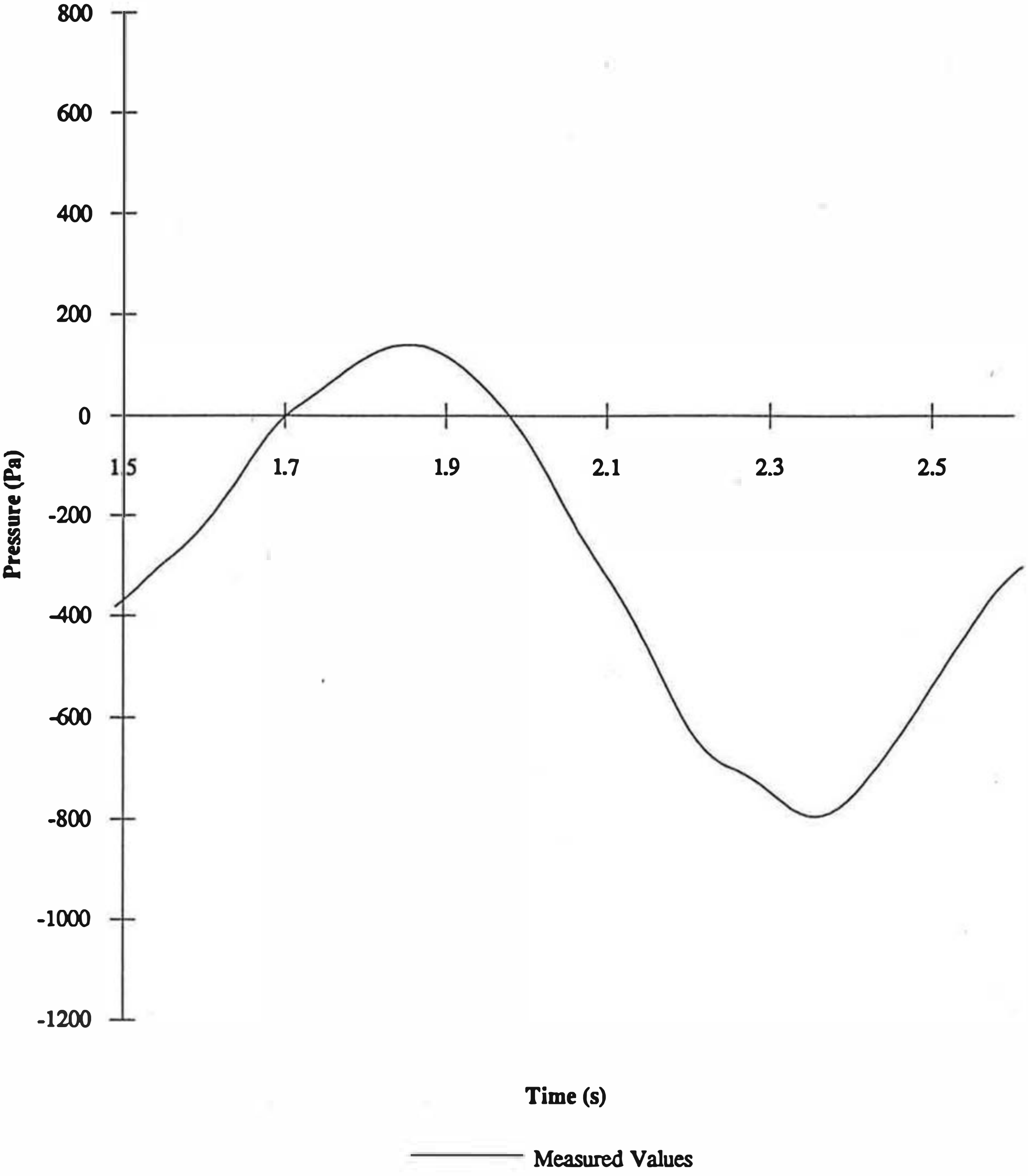
Yeovil Vent: Period=2.2s, -103 Pa Applied Pressure



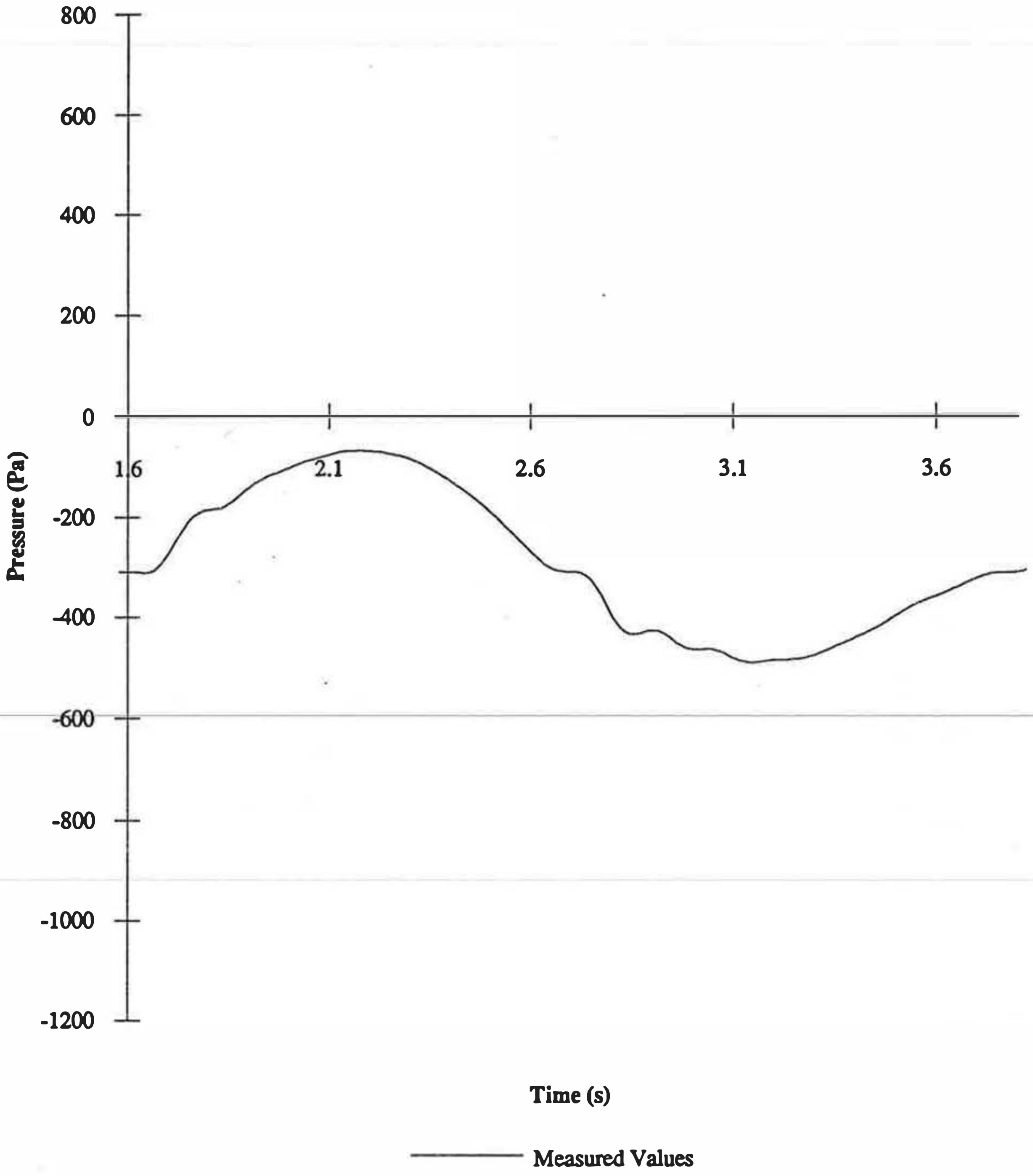
Yeovil Vent: Period=5.3s, -101 Pa Applied Pressure



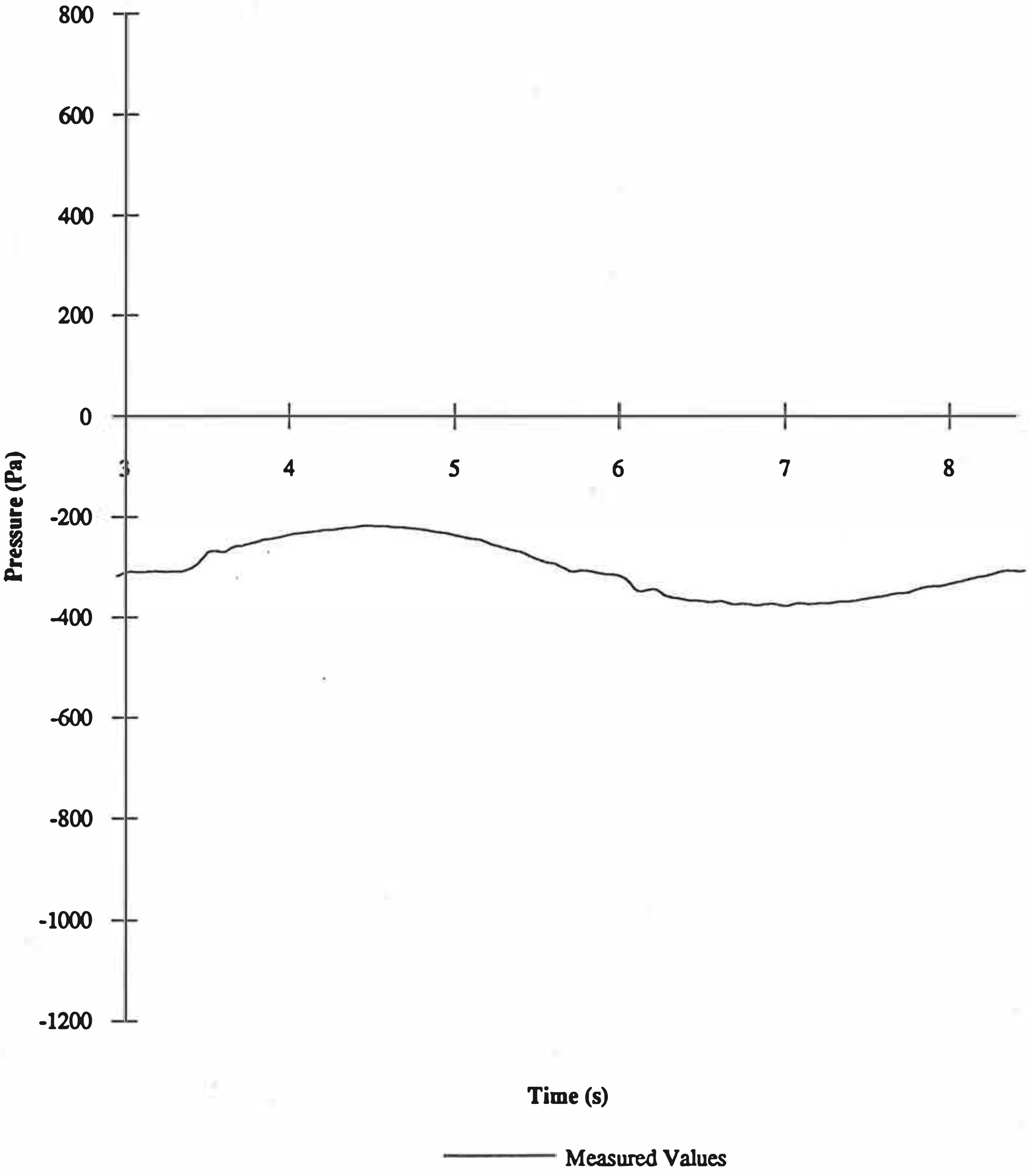
Yeovil Vent: Period=1.1s, -311 Pa Applied Pressure



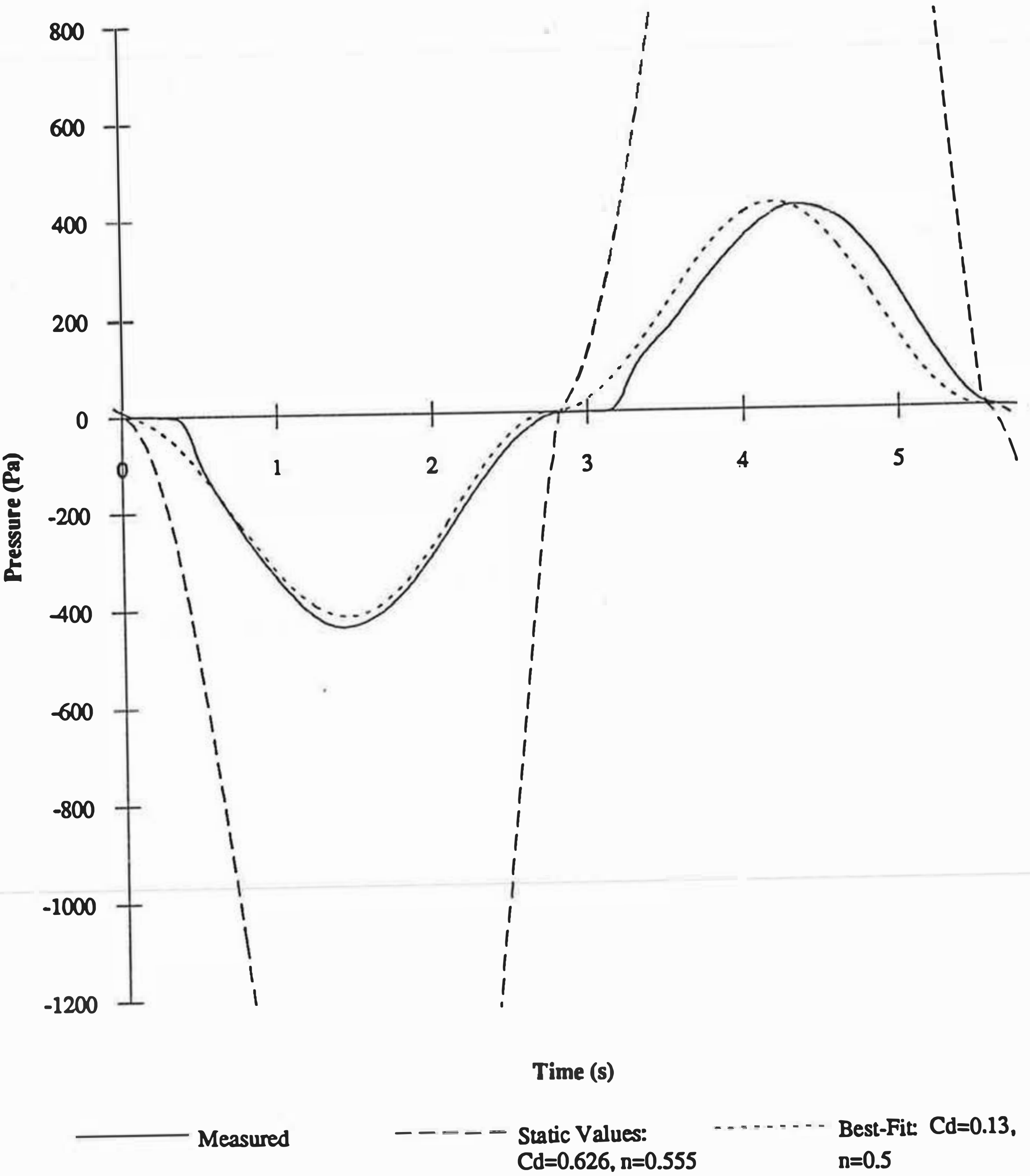
Yeovil Vent: Period=2.2s, -312 Pa Applied Pressure

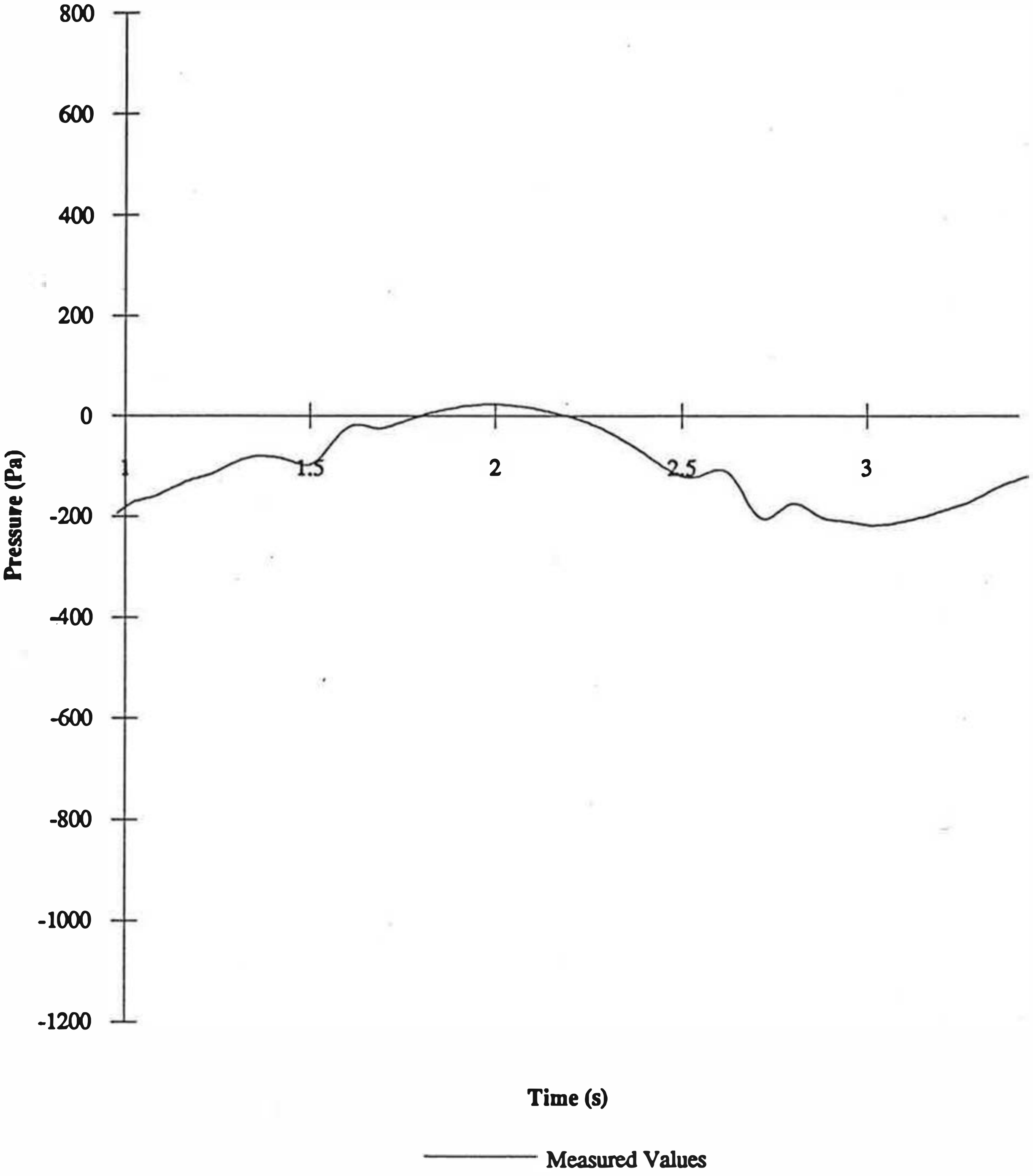


Yeovil Vent: Period=5.2s, -309 Pa Applied Pressure



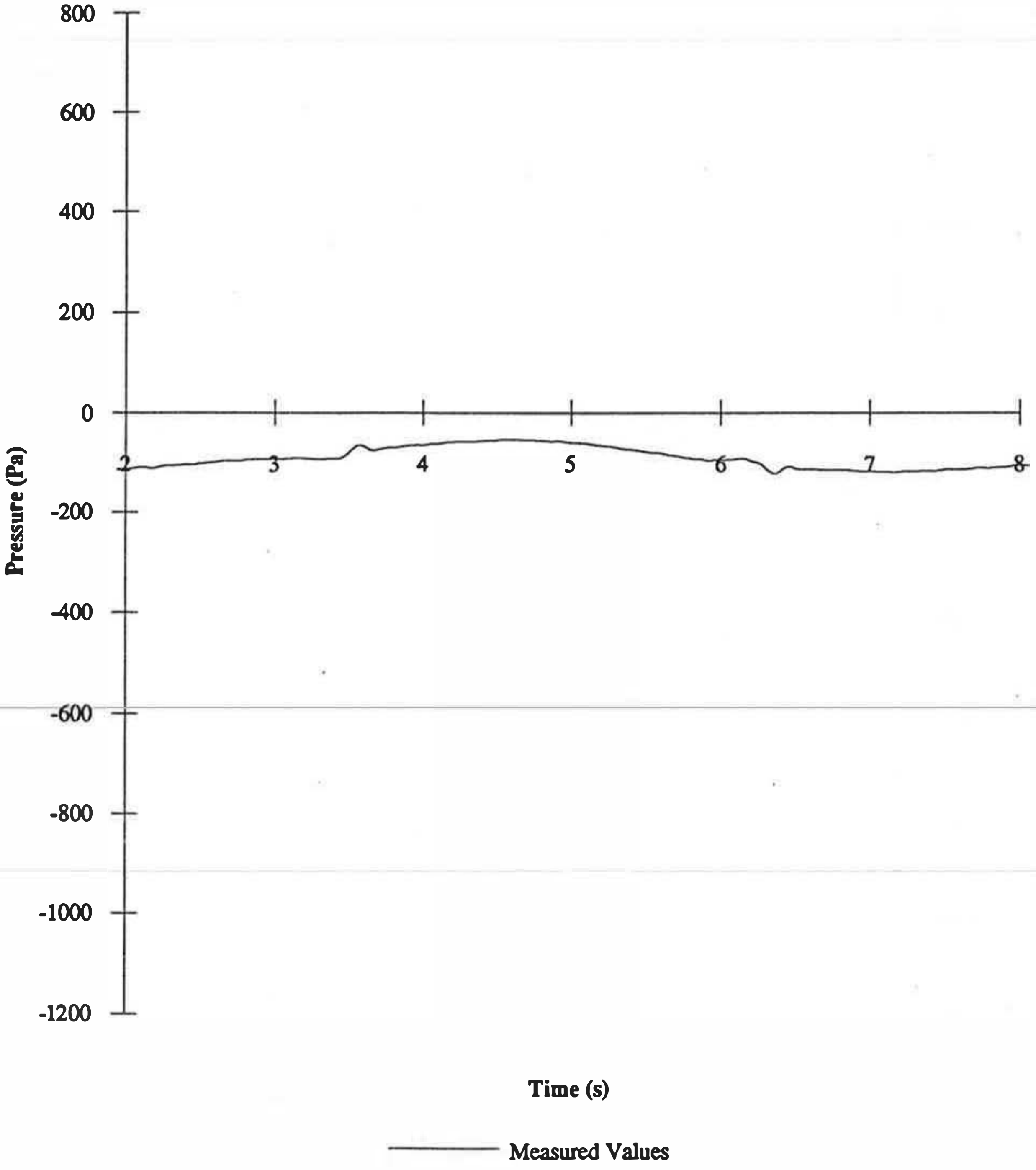
Aircraft Style Vent: Period=5.5s, No Applied Pressure



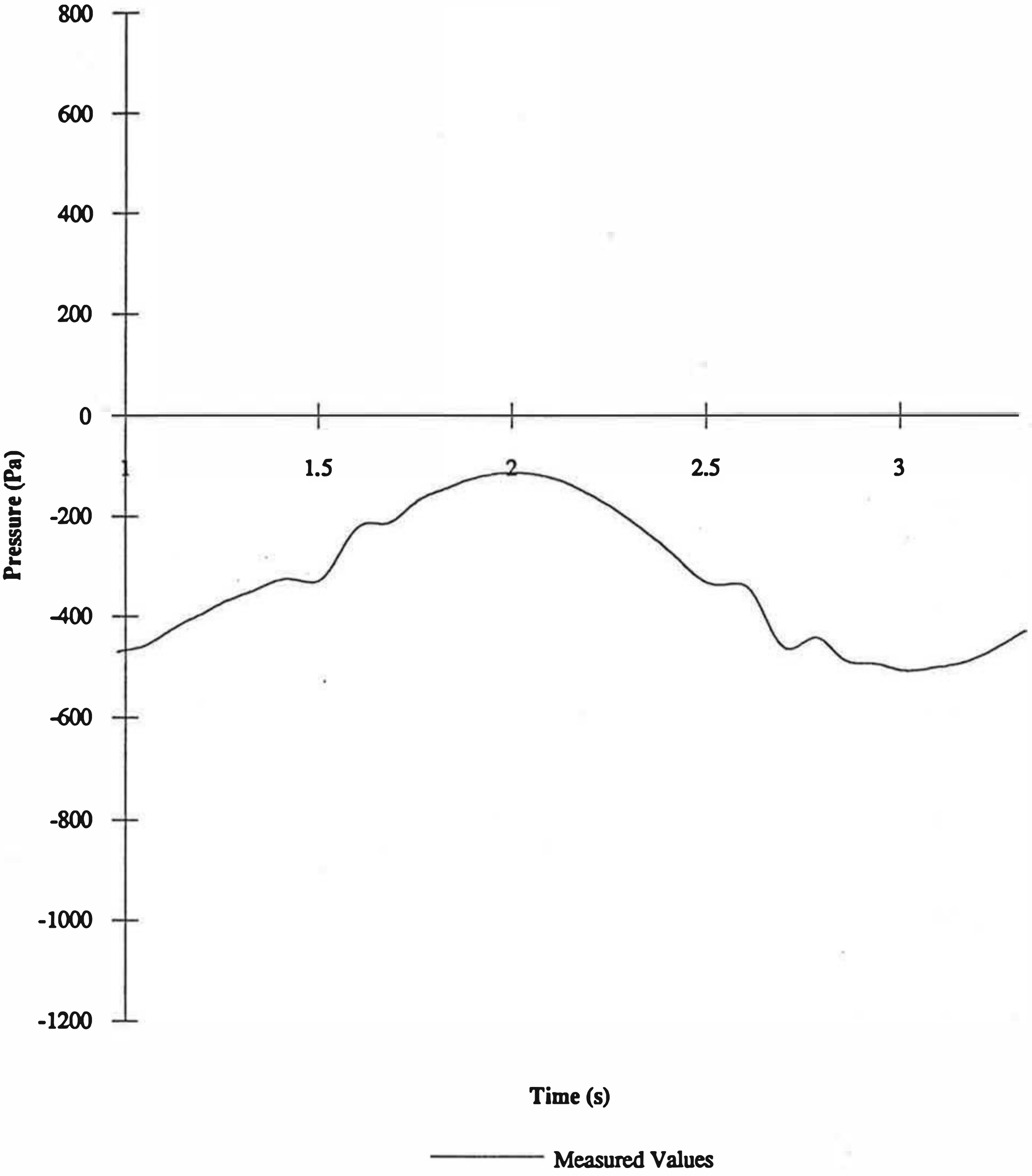


Aircraft Style Vent: Period=2.2s, -103 Pa Applied Pressure

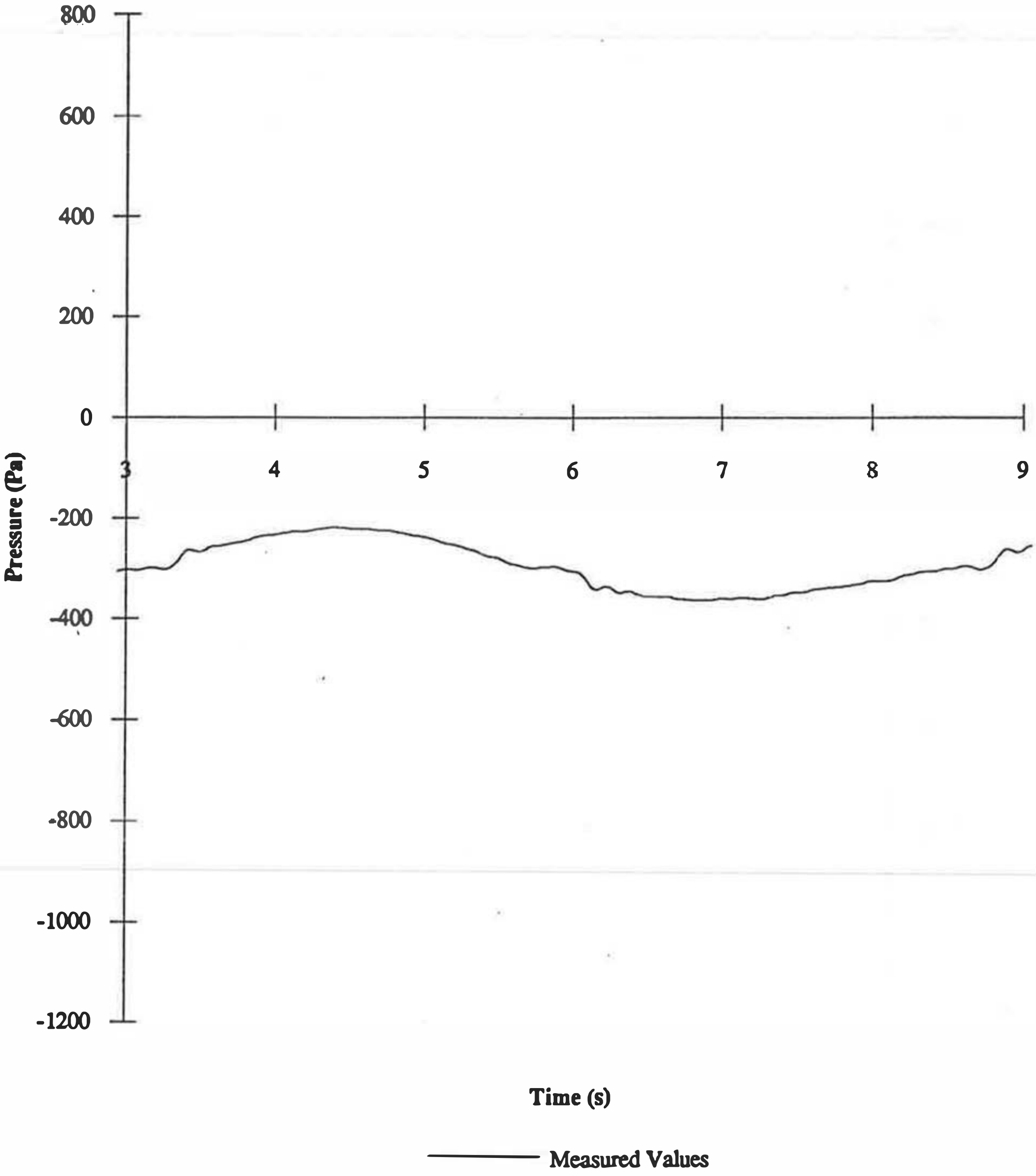
Aircraft Style Vent: Period=5.6s, -95 Pa Applied Pressure



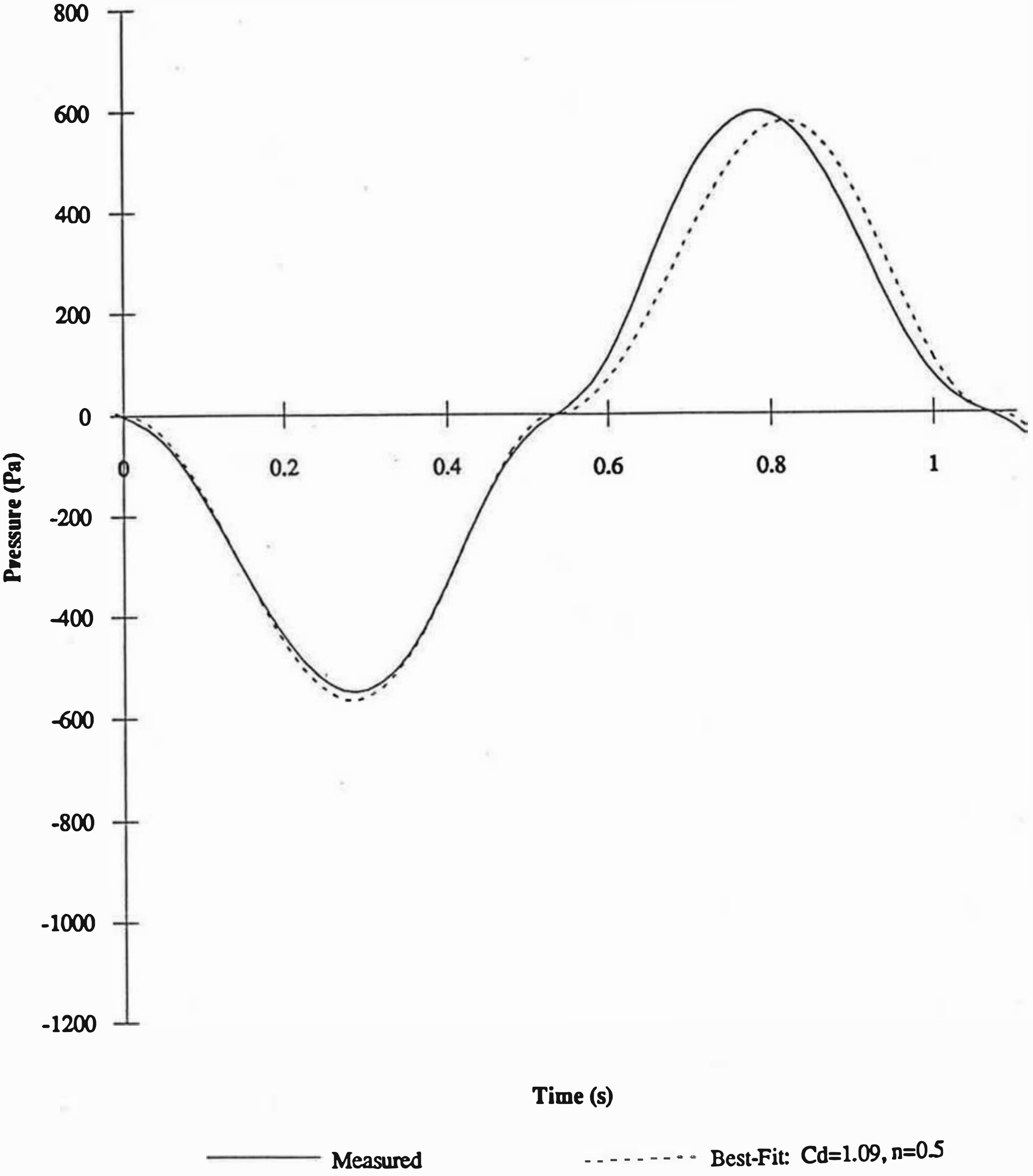
Aircraft Style Vent: Period=2.2s, -339 Pa Applied Pressure

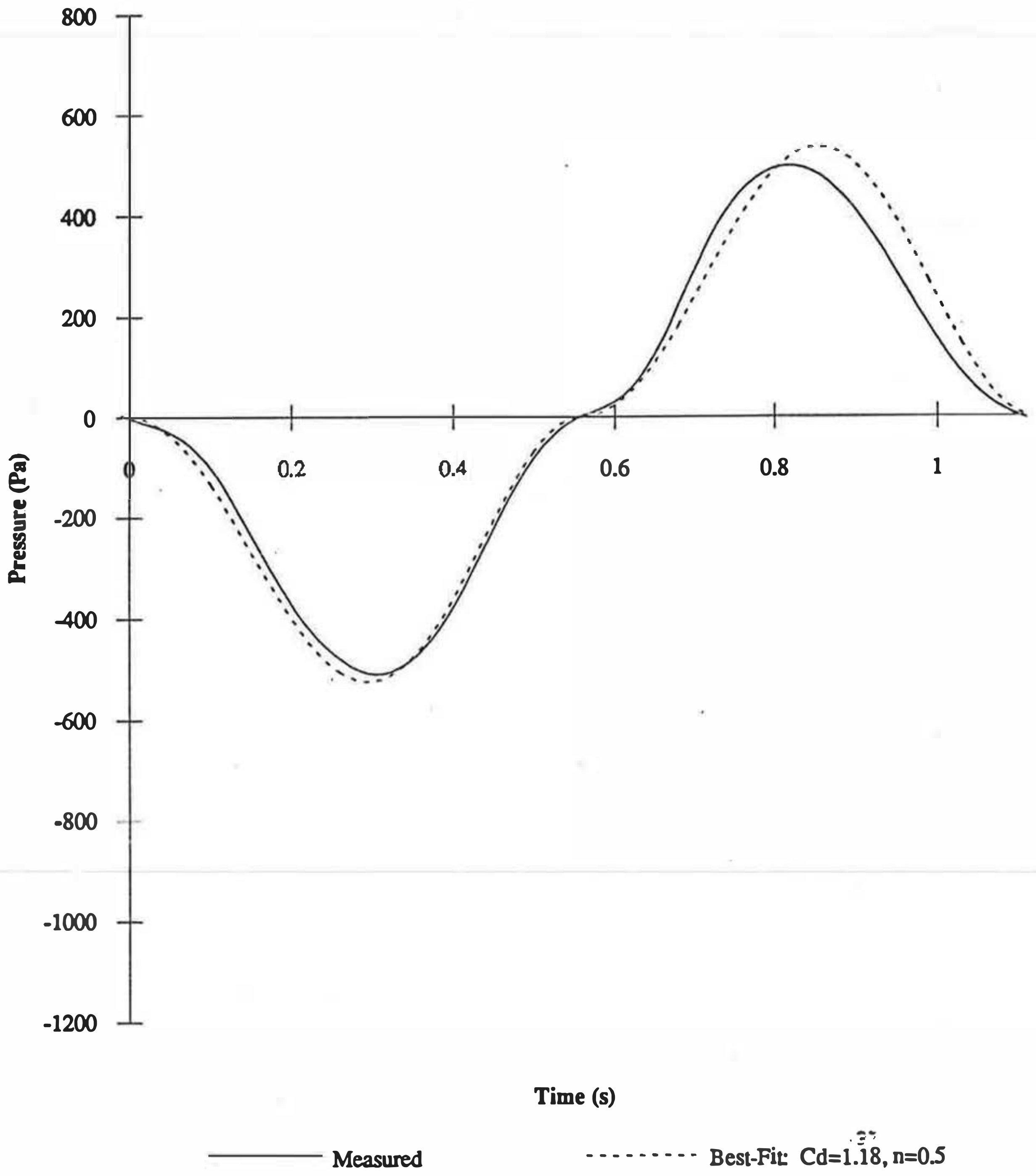


Aircraft Style Vent: Period=5.5s, -300 Pa Applied Pressure



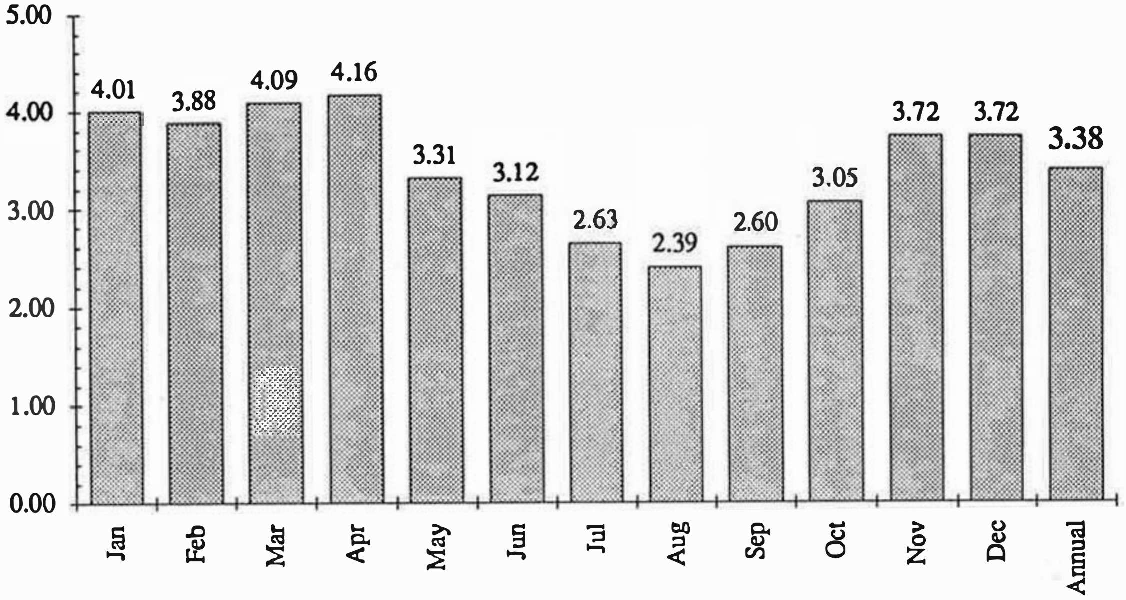
22.6 mm Orifice: Period=1.1 s, No Applied Pressure



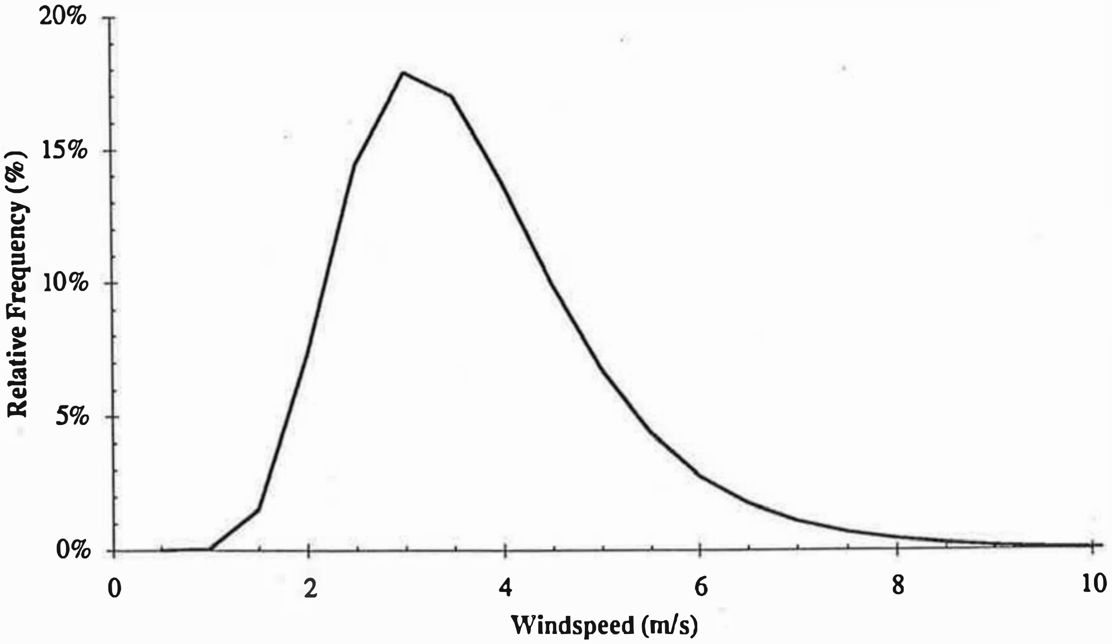

90 mm Pipe: Period=1.1s, No Applied Pressure

Appendix C

Selected Summary Statistics of Wind Speed, Wind Direction, and Ventilation Pressures Measured at the Beghut

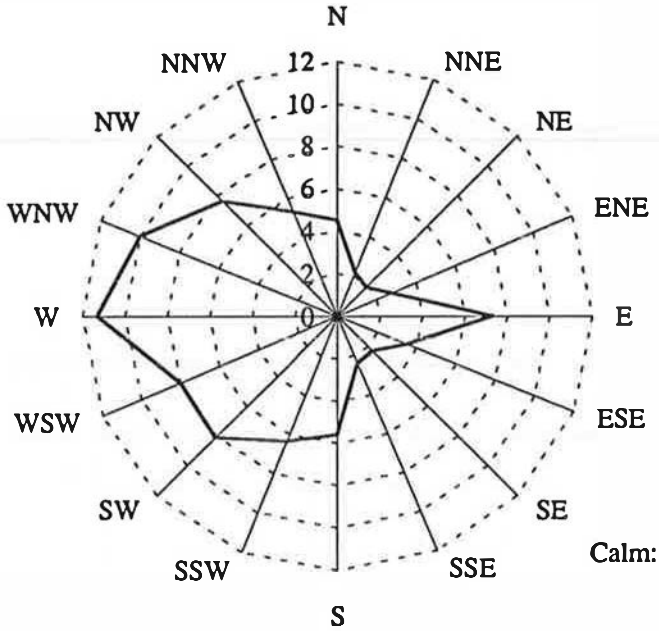


Monthly Average Windspeed [m/s] (Waterloo-Wellington Airport Normals)



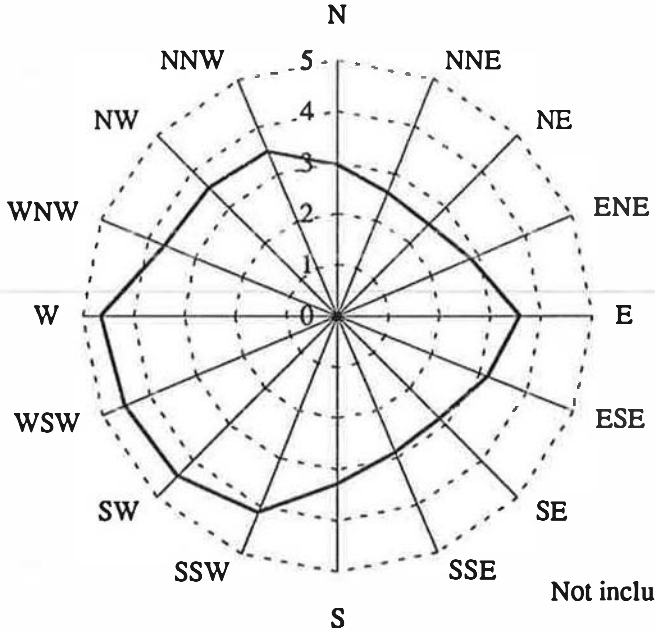
Windspeed Probability Distribution

Wind Direction Frequency for Waterloo (%)

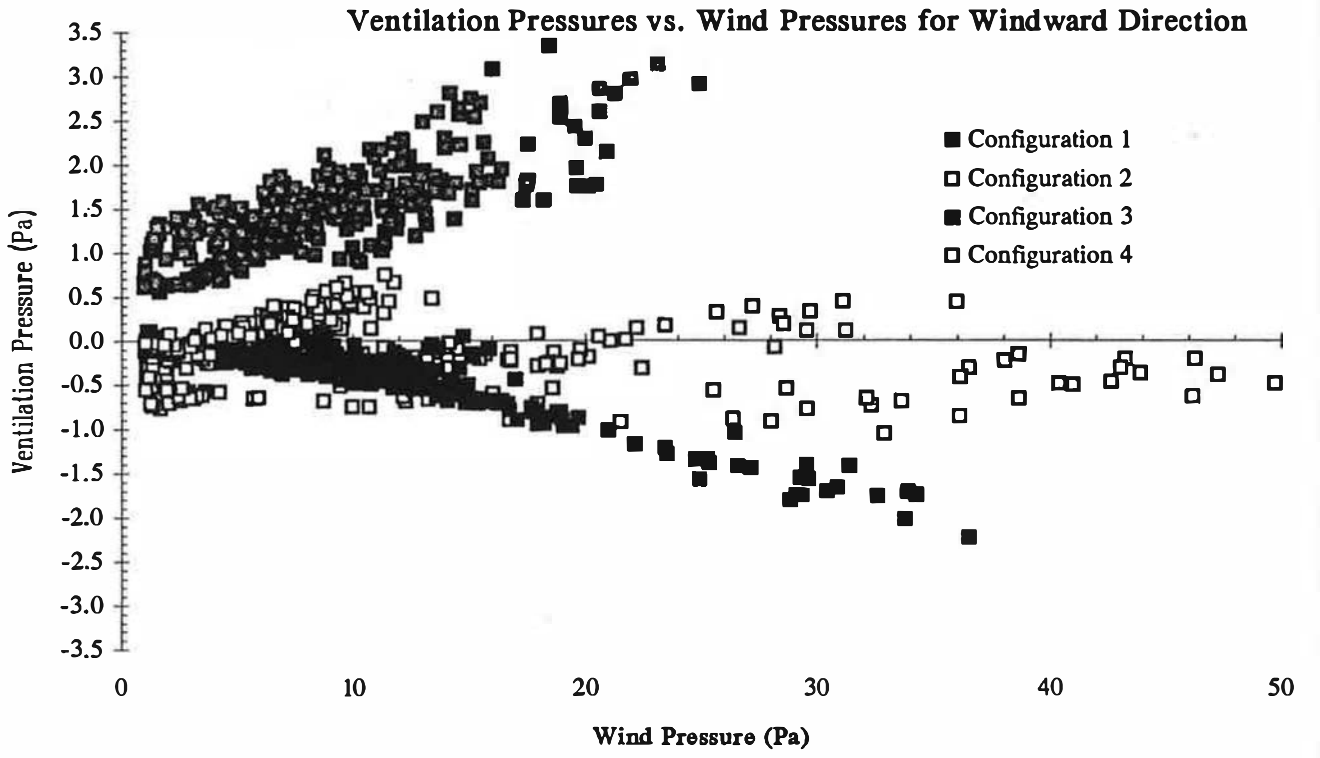


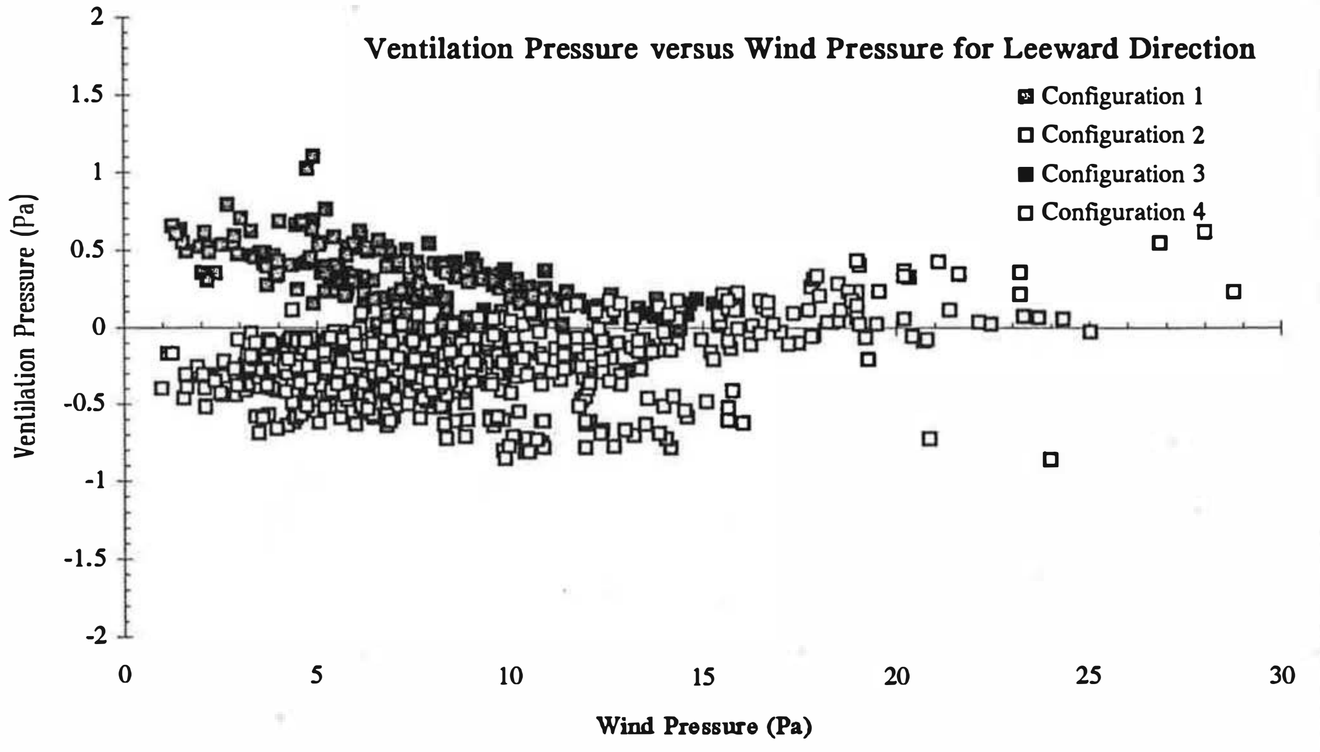
Calm: 10.4%

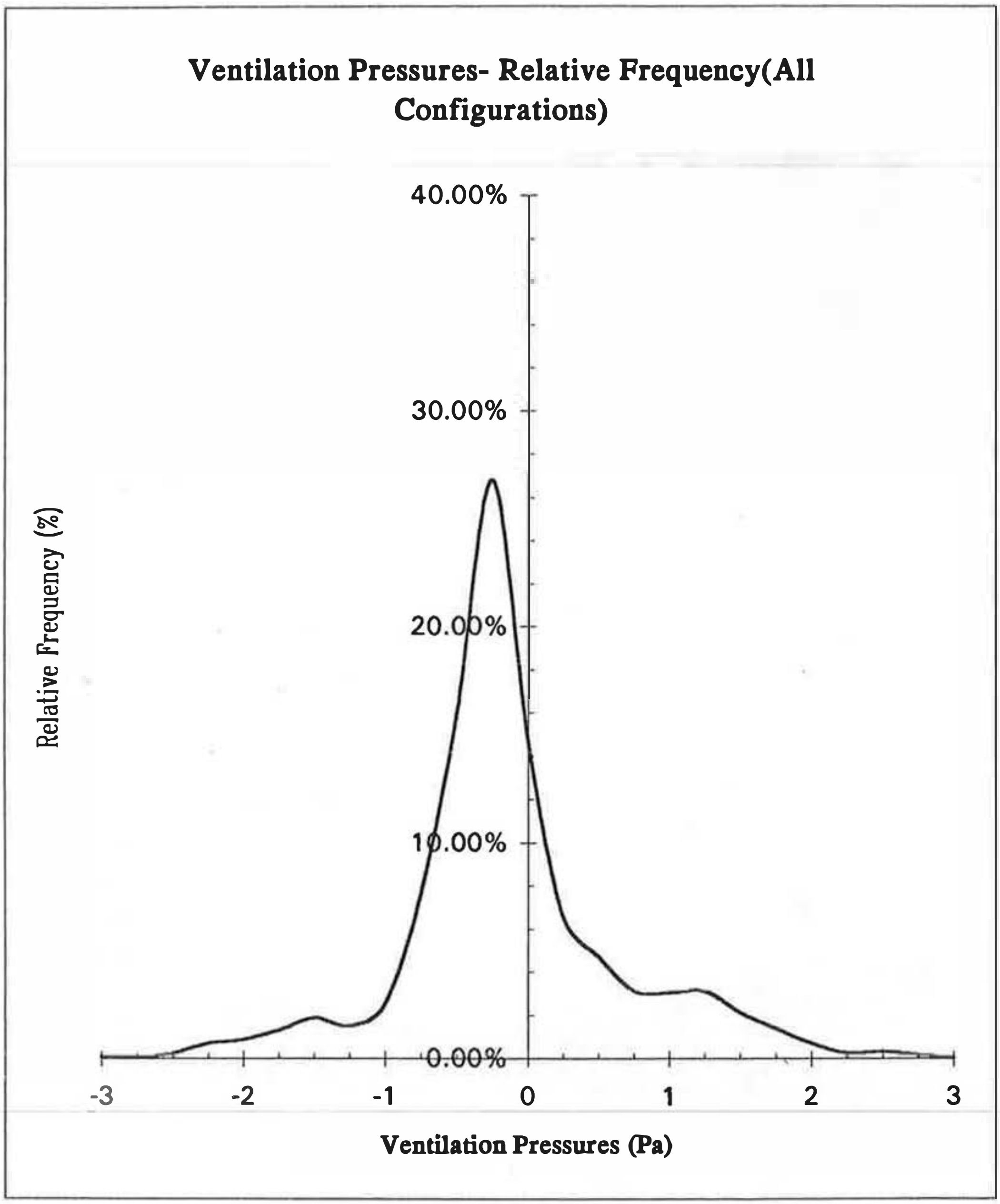
Waterloo Average Wind Speed (m/s)



Not including10.4% calm hours

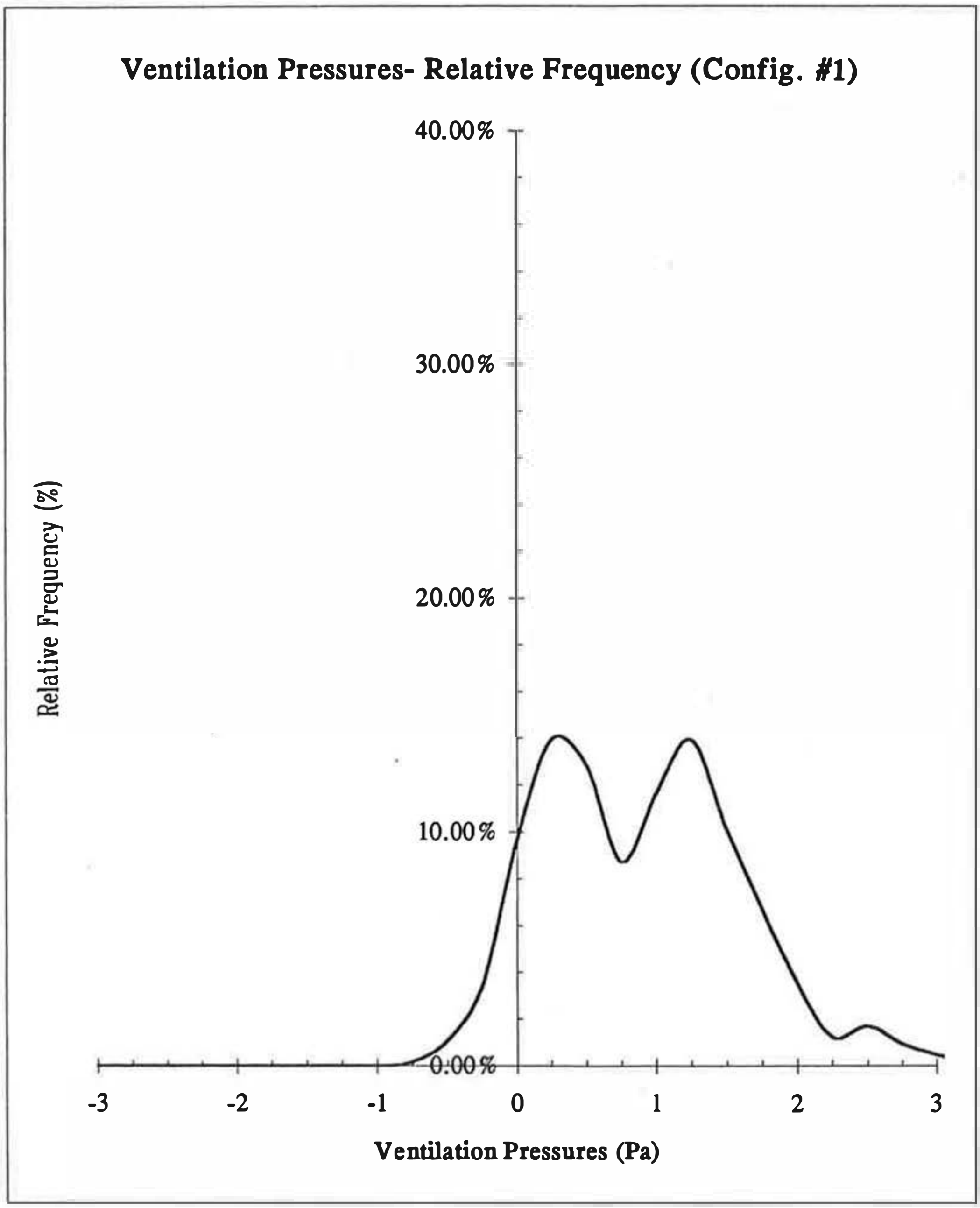

Ventilation Pressures vs. Wind Pressures for Windward Direction
■ Configuration 1
□ Configuration 2
■ Configuration 3
□ Configuration 4
Ventilation Pressure (Pa)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
0
10
20
30
40
50
Wind Pressure (Pa)


Ventilation Pressure versus Wind Pressure for Leeward Direction
▨ Configuration 1
□ Configuration 2
■ Configuration 3
□ Configuration 4
Ventilation Pressure (Pa)
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0
5
10
15
20
25
30
Wind Pressure (Pa)



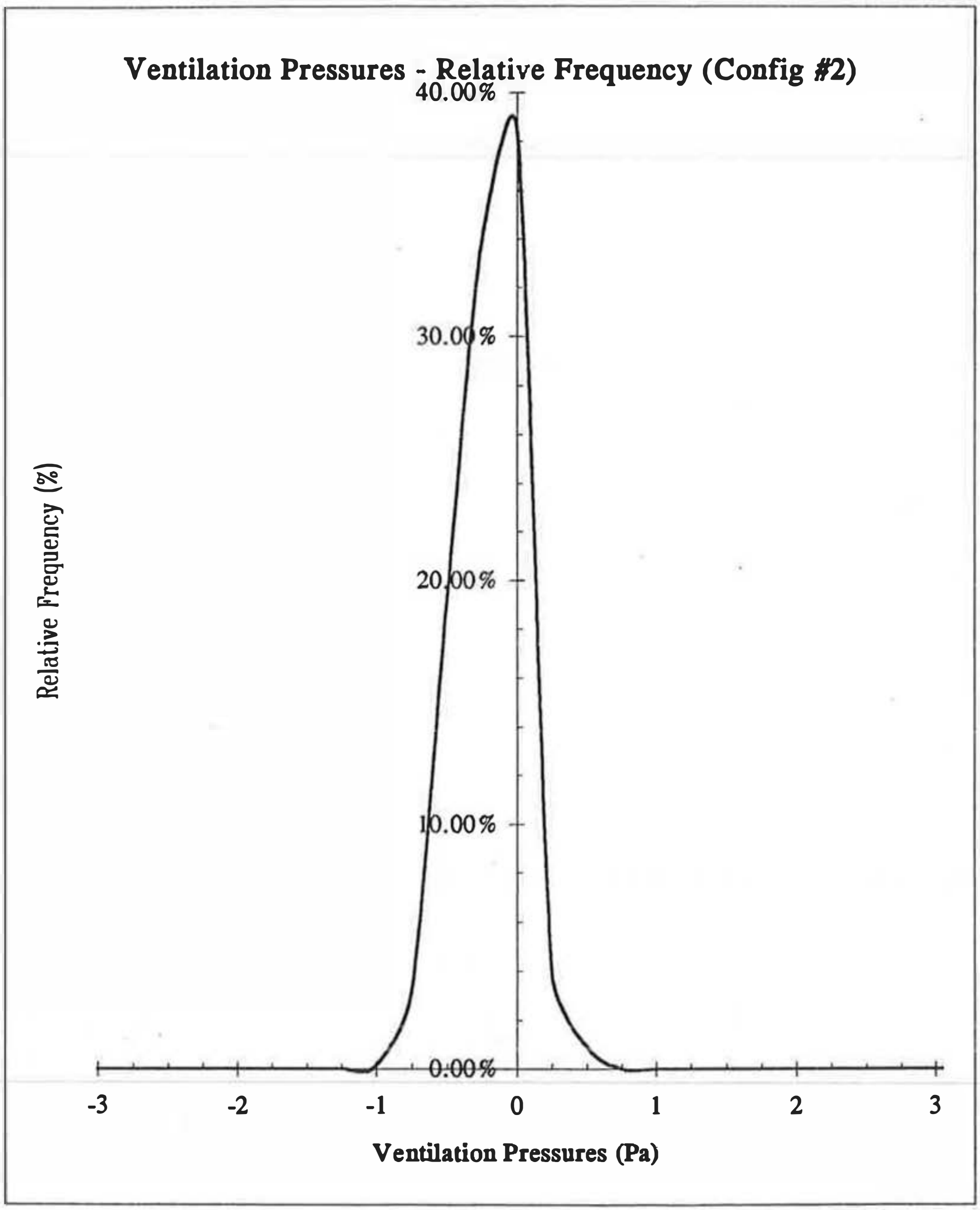
Ventilation Pressures- Relative Frequency(All Configurations)

	VENTavg	VENTrms	VENTmax	VENTmin
Average	0.006	0.904	3.730	-3.915
RMS	0.775	1.139	3.811	5.086
Max	3.330	8.662	12.480	1.030
Min	-3.000	0.020	-0.620	-17.380
Range	6.330	8.642	13.100	18.410
Total Number of Records:		3287		



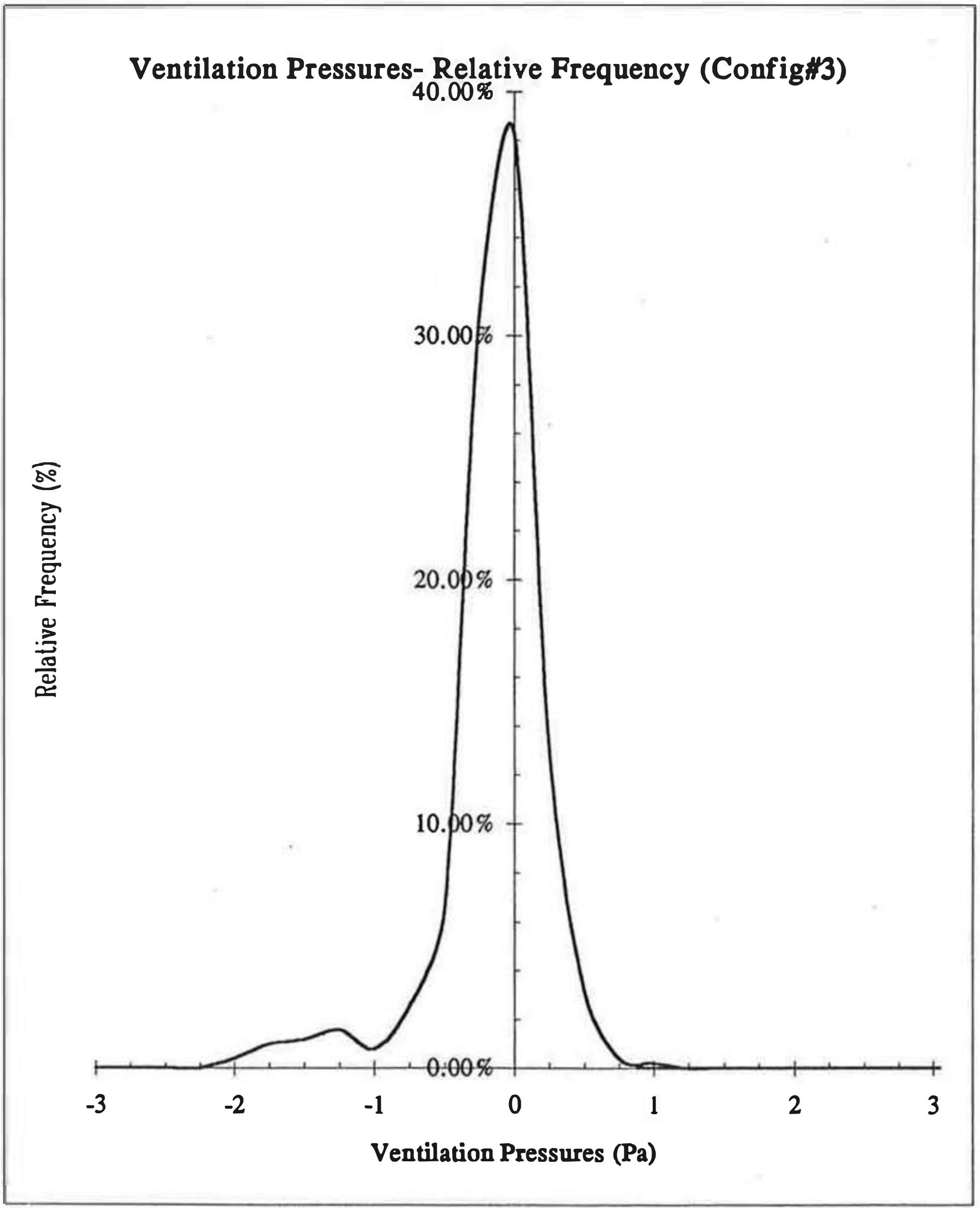
Ventilation Pressures- Relative Frequency (Config. #1)

	VENTavg	VENTrms	VENTmax	VENTmin
Average	1.014	0.500	3.422	-0.461
RMS	0.701	0.379	2.691	1.438
Max	3.330	1.827	11.850	1.030
Min	-0.510	0.049	0.420	-16.770
Number:	654			

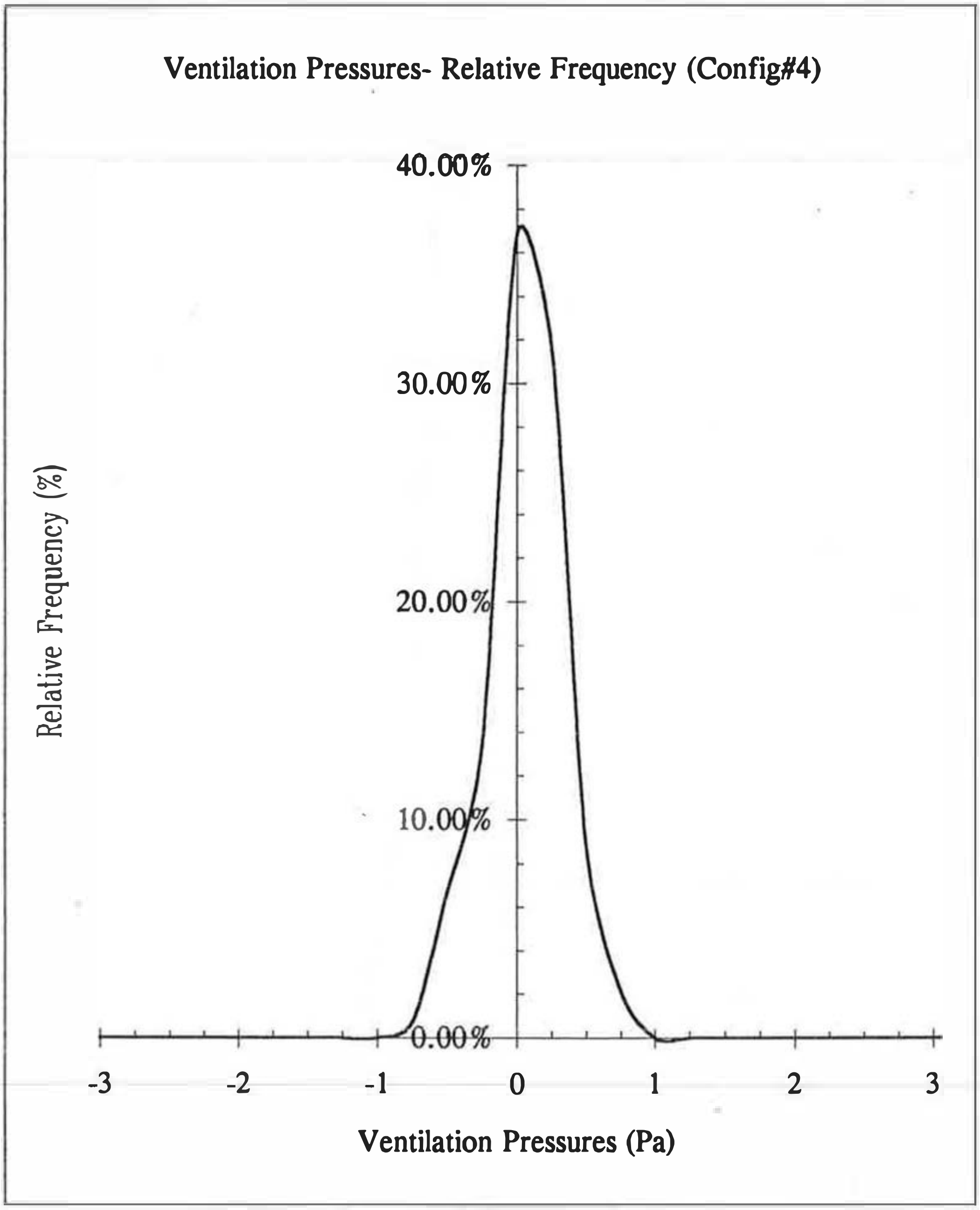


Ventilation Pressures - Relative Frequency (Config #2)

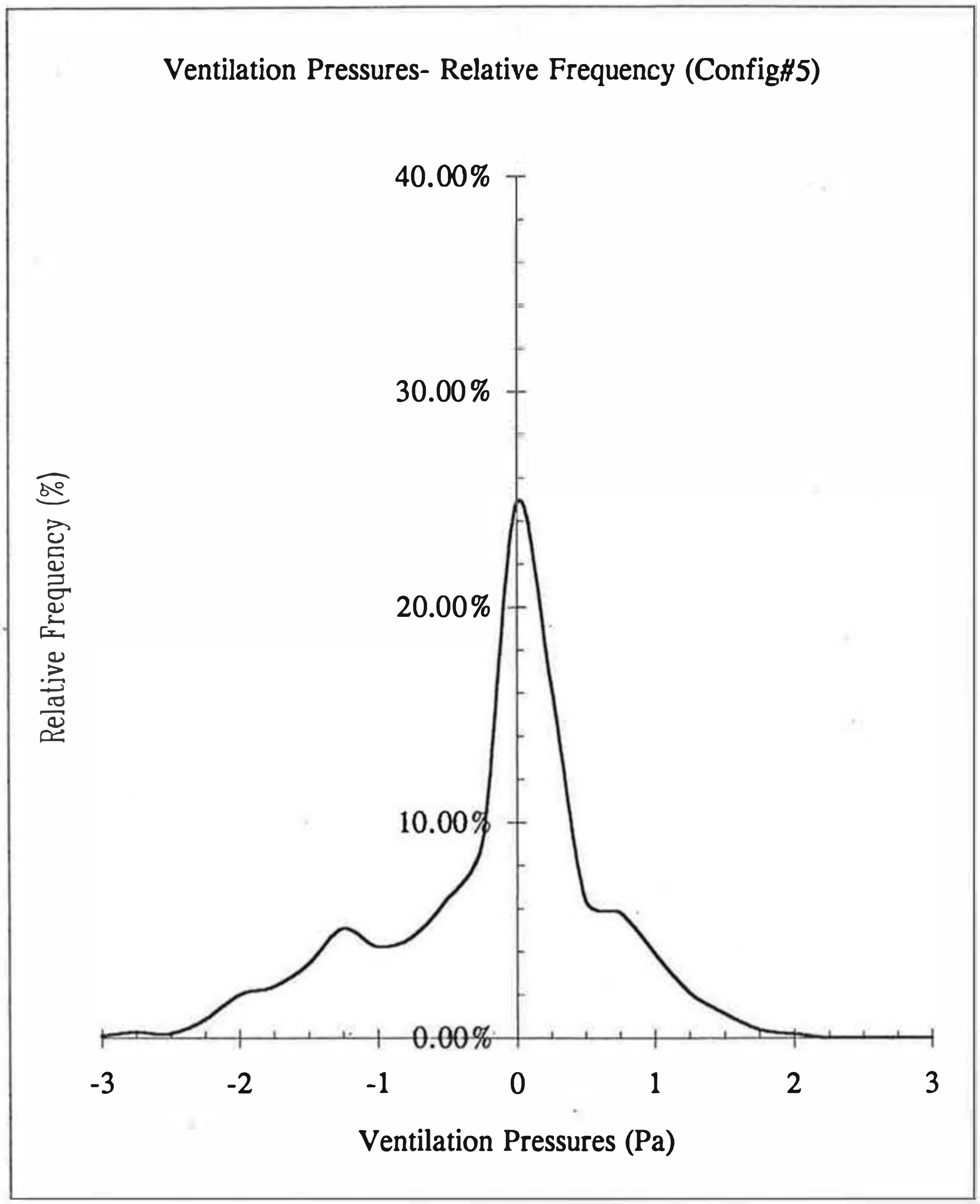
	VENTavg	VENTrms	VENTmax	VENTmin
Average	-0.308	0.402	1.493	-2.403
RMS	0.230	0.533	2.321	2.930
Max	0.440	3.537	11.900	-0.270
Min	-1.060	0.023	-0.620	-16.570
Number:	658			


Ventilation Pressures- Relative Frequency (Config#3)

	VENTavg	VENTrms	VENTmax	VENTmin
Average	-0.262	0.483	1.792	-2.863
RMS	0.388	0.456	1.727	2.908
Max	0.770	3.026	9.880	0.010
Min	-2.230	0.020	0.000	-16.060
Number:	507			



	VENTavg	VENTrms	VENTmax	VENTmin
Average	-0.053	0.542	2.715	-2.506
RMS	0.274	0.319	2.055	1.651
Max	0.750	1.723	10.270	-0.270
Min	-0.860	0.041	-0.010	-8.770
Number:	421			



	VENTavg	VENTrms	VENTmax	VENTmin
Average	-0.272	1.820	6.676	-8.098
RMS	0.797	1.558	4.522	6.454
Max	1.850	8.662	12.480	-0.070
Min	-3.000	0.027	-0.450	-17.380
Number:	1047			