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Reduction of Air Intake Contamination in High-Rise Residential Buildings: Final Report

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Reduction of Air Intake Contamination in

High-Rise Residential Buildings

by

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Final Report

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ABSTRACT

An experimental study has been carried out to evaluate the risk of contamination of fresh air intakes of high-rise residential buildings due to the emission of pollutants from an adjacent building. Design guidelines were developed to assist engineers in the placement of stacks and inlets.

Flow visualization experiments performed using a water channel showed that contamination of air intakes on a high-rise building can occur if pollutants are emitted from a smaller building that is directly upwind or downwind. These results were confirmed by a series of tracer gas experiments carried out in a wind tunnel. This study showed that potential for intake contamination is highest when the two buildings are attached.

The effects of various parameters on intake contamination were evaluated. These included adjacent building height, separation distance between the two buildings, stack height and stack location. For each building configuration tested, the severity of potential intake contamination was evaluated by comparing dilution data with minimum dilution values obtained from a widely-used ASHRAE model which has been found to give conservative predictions of minimum dilution. Those configurations that produced dilution values lower than those of the ASHRAE model were deemed to be problematic.

For the case of the downwind emitting building, the crosswind width (L) of the adjacent building was found to have a significant effect on the potential for intake contamination. The severity of contamination was found to be higher for a wide building (L=60 m) than a narrow building (L=30 m), due to the large wake of the former.

When the height of the adjacent building is more than 20 m greater than that of the emitting building, increasing stack height will provide only marginal benefit. The study found that, for some stack locations, maximum concentrations on the wall of the adjacent building were not significantly reduced even when the stack height was increased to 10 m.

EXECUTIVE SUMMARY

A fluid modeling study has been carried out to evaluate various high-rise residential building configurations with respect to the likelihood of reingestion of building exhaust at fresh air intakes. Design guidelines were developed to assist engineers in the placement of stacks and inlets. The study focused on moderately tall buildings of 15 to 30 stories.

Preliminary flow visualization experiments were carried out in a water channel to identify building arrangements that can lead to reingestion problems. This study showed that when the emitting building was upwind or downwind of a **taller** building, wall air intakes on the adjacent and emitting buildings may experience low dilution of emissions due to direct plume contact or plume entrapment in a recirculation zone. Based on the flow visualization tests, a series of wind tunnel experiments were performed to provide quantitative dilution data.

In the wind tunnel study, the emitting building had a full-scale height, H, of 54 m (~16 stories) and a width, W, of 30 m. Most tests were performed with a taller adjacent building placed either upwind or downwind of the emitting building with the wind direction perpendicular to the front face of the building.

The influence of various parameters on plume behavior was investigated. These include:

Adjacent building height (H_a =1.3H, H_a=1.7H, H_a=2H)

Adjacent building width (W_a=W, W_a=2W)

Building separation (S=0, S=W, S=2W)

Wind direction (θ=0°, θ=45°)

Stack location (center, upwind edge, downwind edge, corner)

A tracer gas (sulfur hexafluoride) was emitted from a stack that was usually located at the center of the roof. The stack was flush with the roof in most tests, and thus, the test results can be considered to be conservative. Likewise, a conservative value of the exhaust momentum ratio, the ratio of exhaust speed to wind speed, was chosen for all tests (M=2). Full-scale equivalent stack heights up to 10 m were also tested. Air samples were obtained at wall locations on the emitting building and the adjacent building. The sample locations represented typical receptor locations of high-rise residential buildings (e.g. fresh air intakes, openable windows)

For each building configuration, the potential for reingestion was evaluated by comparing wind tunnel dilution data with minimum dilution values obtained from a widely-used ASHRAE model which has been found to give conservative predictions of minimum dilution. Those configurations that produced dilution values lower than those of the ASHRAE model were deemed to be problematic. Depending on the type of contaminant, some mitigation measures could be required for these configurations.

The tracer gas experiments show that significant reingestion of building exhaust is most likely for two building arrangements. These are:

Configuration A: the emitting building upwind of a taller adjacent building, and

Configuration B: the emitting building downwind of a taller adjacent building

The study has shown that for configuration A, the potential for reingestion is most severe if no gap exists between the buildings (S=0). In this case, measured dilution values at some locations on the adjacent wall approached the ASHRAE minimum dilution values. An increase in separation distance to S=30 m produced dilution values on the adjacent building that were much larger than those predicted by the ASHRAE model.

The presence of the taller building downwind reduced dilution significantly on the leeward wall of the emitting building when the separation distance was small ($S \leq 30$ m). Dilution values were approximately a factor of 5 lower than those obtained on the leeward wall of an isolated building. Dilution levels on the lower wall of the emitting building were approximately equal to the ASHRAE minimum dilution values for S=30 m. However, when S was increased to 60 m, dilution values approached those obtained with the isolated building.

Configuration B experiments showed that reingestion problems may also be severe if no gap exists between the buildings (S=0). Measured dilution values at some locations on the adjacent wall approached the ASHRAE minimum dilution values. It should also be noted that, unlike configuration A, configuration B with S=0 produced low dilution values over the entire wall of the adjacent building rather than at a localized area.

The crosswind width (L) of the upwind adjacent building was found to have a significant effect on dilution measured on its leeward wall. The narrow upwind building (L=30 m) produced relatively high dilution values when the buildings were separated by a gap of 30 m. However, increasing the width of the adjacent building to 60 m caused a significant reduction in dilution, especially for the tallest building. Dilution measurements on the leeward wall of the double-width building for S=30 m were similar in magnitude to the predicted values obtained with the ASHRAE model. The decrease in dilution for the wide building is due to a significant increase in both the along-wind depth and the height of the wake of the building.

Guidelines have been provided to assist the designer in identifying building configurations that could potentially result in reingestion problems. The guidelines describe the configurations in terms of the height difference, ΔH, and the separation distance, S, between the buildings.

Configuration A: Emitting building upwind of taller adjacent building

For buildings with a large height difference ($\Delta H > 20$ m), the plume from the upwind building travels downwards when it contacts the windward wall of the adjacent building. In this case, increasing the stack height or flow rate to increase the plume height would be impractical in most cases. On the other hand, when the height difference is small ($\Delta H < 20$ m), plume contact with the adjacent wall, if it occurs, will be near the roof. In this case, the designer has the option to increase stack height or flow rate so that the plume will travel over the adjacent building.

In terms of separation distance, Type A configurations were classified as S=0 (no gap) or S<30 m (small gap less than the building width, W). The no gap case is the most problematic for receptors on the windward wall of the adjacent building, with dilution levels approaching those predicted by the conservative ASHRAE minimum dilution model.

When a small gap exists between the buildings, dilution values on the adjacent building wall will be higher than those for the no-gap case. On the other hand, this configuration may cause reingestion to occur at air intakes on the leeward wall of the upwind emitting building. Dilution values on the leeward wall of the emitting building are significantly reduced by the presence of a taller adjacent building, compared to those obtained with an isolated building.

Configuration B: Emitting building downwind of taller adjacent building

A dividing limit of ΔH=20 m was also chosen for Type B configurations. In this case, plume rise is unpredictable but should be relatively large due to the sheltering effect of the upwind building. For small ΔH (< 20 m), reingestion may be avoided for the most part by raising the stack and/or increasing the flow rate. However, for large ΔH, these design alternatives will probably not be practical.

Type B configurations were classified as S = 0 (no gap), S < 30 m (small gap less than the typical width of an adjacent tall building) and 30 m < S < 60 m. When no gap exists between the buildings, dilution values on the leeward wall of the taller upwind building will be relatively low. Minimum dilution values will approach those predicted by the conservative ASHRAE dilution model. Increasing the distance between the buildings may significantly increase dilution values on the adjacent building wall, depending on the width of the upwind building. For a relatively narrow upwind adjacent building (W=30 m), dilution values on its leeward wall will be significantly higher than those predicted by the ASHRAE minimum dilution formula even for a relatively small gap of 30 m. On the other hand, a wide building (W=60 m) upwind of the emitting building will require greater separation to obtain high dilution levels on the adjacent building wall.

RÉSUMÉ

Une étude de modélisation des fluides sur différentes configurations de tours d'habitation a été réalisée afin d'évaluer les risques d'ingestion d'air vicié par les prises d'air frais. Des directives de conception ont été élaborées afin d'aider les ingénieurs à concevoir l'emplacement des bouches d'évacuation et des prises d'air de bâtiments de moyenne hauteur comportant de 15 à 30 étages.

Des études préliminaires de visualisation des débits ont été menées en bassin afin de découvrir les configurations de bâtiments pouvant causer l'ingestion d'air vicié. L'étude dont il est question ici a révélé que lorsqu'un bâtiment émetteur se situe en amont ou en aval d'un bâtiment **plus élevé**, les prises d'air murales sur un bâtiment voisin et sur le bâtiment émetteur pouvaient être exposées à une faible dilution des émissions à cause d'un contact direct avec le panache ou de l'emprise sur le panache par une zone de recirculation. Sur la base des essais de visualisation des débits, on a effectué une série d'essais en soufflerie afin d'obtenir des données quantitatives sur la dilution.

Dans les analyses en soufflerie, le bâtiment émetteur avait une hauteur à l'échelle, H, de 54 m (environ 16 étages) et une largeur, W, de 30 m. Lors de la plupart des essais, le bâtiment plus élevé était situé en amont ou en aval du bâtiment émetteur, et la direction du vent était perpendiculaire à la façade du bâtiment.

Différents paramètres et leurs effets sur le comportement du panache ont été examinés :

Hauteur du bâtiment voisin (Ha =1.3H, Ha=1.7H, Ha=2H)

Largeur du bâtiment voisin (Wa=W, Wa=2W)

Distance entre les bâtiments (S=0, S=W, S=2W)

Direction du vent (0° et 45°)

Emplacement des sorties d'évacuation (au centre, en bordure en amont, en bordure en aval, dans un angle)

Un gaz de dépistage (hexafluorure de soufre) a été employé dans une sortie d'évacuation d'essai située habituellement au centre de la toiture. La sortie était à ras de la toiture dans la plupart des essais, on peut donc supposer que les essais sont plutôt conservateurs. Dans la même veine, lors de tous les essais, on a choisi une valeur conservatrice de 2 pour le rapport d'impulsion des gaz, M, le rapport entre la vitesse des gaz et celle du vent. Les chercheurs ont également mis à l'essai des sorties d'évacuation allant jusqu'à 10 m de hauteur à l'échelle. Des échantillons d'air ont été prélevés près des murs du bâtiment émetteur et du bâtiment voisin. Les emplacements choisis pour l'échantillonnage sont un reflet fidèle de l'emplacement de récepteur typiques dans une tour d'habitation, c.-à-d. les prises d'air frais et les fenêtres.

Pour chaque configuration de bâtiment, la possibilité d'ingestion a été évaluée en comparant les données de dilution des essais en soufflerie avec les données minimales de dilution obtenues à l'aide du modèle bien connu de l'ASHRAE, lequel donne des prévisions conservatrices du taux minimal de dilution. Les configurations qui ont engendré des valeurs de dilution inférieures au modèle ASHRAE ont été jugées problématiques. Selon le contaminant en présence, certaines mesures d'atténuation pourraient être requises pour ces configurations.

Les essais réalisés à l'aide des gaz de dépistage montrent q'une ingestion importante d'air vicié est le plus probable pour deux arrangements de bâtiments :

Configuration A : bâtiment émetteur situé en amont d'un bâtiment voisin plus élevé et
Configuration B : bâtiment émetteur situé en aval d'un bâtiment voisin plus élevé

L'étude a établi que pour la configuration A, la possibilité d'ingestion est la plus grande si la distance entre les bâtiments est nulle (S égale 0). Dans ce cas, les valeurs de dilution mesurées à certains endroits sur le mur voisin s'approchaient des valeurs de dilution minimales de l'ASHRAE. Une augmentation à 30 m de la distance S entre les bâtiments a produit des valeurs de dilution sur le bâtiment voisin qui étaient de beaucoup supérieures aux valeurs prévues par le modèle ASHRAE.

La présence d'un bâtiment plus élevé en aval a réduit la dilution de manière importante près du mur sous le vent du bâtiment émetteur lorsque la distance qui les sépare est faible (S égale 30 m). La dilution était inférieure par un facteur d'environ 5 sur celle obtenue sur la façade côté vent d'un bâtiment isolé. Pour S égale 0 m, les valeurs de dilution sur la partie inférieure du mur du bâtiment émetteur étaient, à peu de choses près, égales aux valeurs minimales de l'ASHRAE. Toutefois, lorsque S augmente à 60 m, les valeurs de dilution étaient presque les mêmes que celles d'un bâtiment isolé.

Les essais sur la configuration B indiquent que les problèmes d'ingestion peuvent également être importants si la distance entre les bâtiments est nulle (S égale 0). La dilution mesurée à certains endroits sur le mur voisin approchait celle des valeurs minimales de l'ASHRAE. Il est à noter qu'au contraire de la configuration A, la configuration B avec S égale 0, a produit des faibles valeurs de dilution sur la surface entière du mur du bâtiment voisin, plutôt qu'à un endroit précis.

On a découvert que la largeur dans le vent (L) d'un bâtiment voisin en amont avait un effet considérable sur la valeur de dilution mesurée près du mur sous le vent. Le bâtiment étroit en amont (L égale 0 m) affiche des valeurs de dilution relativement élevées lorsque situé à une distance de 30 m. Cependant, le fait d'augmenter la largeur du bâtiment voisin à 60 m a provoqué une importante diminution de la dilution, particulièrement pour l'immeuble le plus élevé. Les lectures de dilution enregistrées près du mur sous le vent du bâtiment à double largeur avec S égal à 30 m étaient du même ordre de grandeur que les valeurs prévues par le modèle ASHRAE. La baisse de dilution près du bâtiment plus large est due à une augmentation considérable de la profondeur du bâtiment dans la direction parallèle au vent et à la hauteur du sillage derrière le bâtiment.

Les chercheurs présentent des lignes de conduite permettant aux concepteurs de mieux repérer les configurations de bâtiments sujets aux problèmes d'ingestion. Elles décrivent les configurations en termes de différence de hauteur, H, ainsi qu'en termes de distance S entre les bâtiments.

Configuration A : Bâtiment émetteur en amont d'un bâtiment voisin plus élevé

Dans les cas de bâtiments comportant une grande différence de hauteur (H > 20 m), le panache provenant du bâtiment en amont se déplace vers le bas au contact du mur côté vent du bâtiment voisin. Dans un tel cas, il serait inutile d'augmenter la hauteur de la sortie d'évacuation ou le débit pour augmenter l'élévation du panache. En revanche, lorsque la différence de hauteur est faible, (H < 20 m), le contact entre le panache et le mur voisin, le cas échéant, ne se produira que près de la toiture. Dans une pareille situation, le concepteur peut choisir d'augmenter la hauteur de la sortie d'évacuation ou le débit de manière à ce que le panache passe au-dessus du bâtiment.

Quant à la distance entre les bâtiments, les configurations de type A ont été regroupées suivant le cas où S égale 0 (espace nul) ou S est inférieur à 30 m (distance de séparation moindre que la largeur du bâtiment, W). Les cas pourvus d'un espace nul sont les plus sujets à problème pour les récepteurs sur les murs côté vent du bâtiment voisin, les niveaux de dilution s'approchant de ceux prévus par le modèle de dilution minimale de l'ASHRAE.

En présence d'un espace restreint entre les bâtiments, les valeurs de dilution sur la paroi du bâtiment voisin seront supérieures à celles comportant un espace nul. D'autre part, cette configuration pourrait provoquer une ingestion d'air vicié à l'endroit des prises d'air du mur sous le vent du bâtiment émetteur qui en amont. Les valeurs de dilution jouxtant le mur sous le vent du bâtiment émetteur seront considérablement réduites par la présence d'un bâtiment plus élevé, comparativement à celles obtenues avec un bâtiment isolé.

Configuration B : Bâtiment émetteur en aval d'un bâtiment voisin plus élevé

Une limite de H égale 20 m a également été choisie pour les configurations de type B. Dans ces cas, la hauteur du panache est imprévisible, mais elle devrait être relativement grande en raison de la protection procurée par le bâtiment en amont. Pour les faibles valeurs de H (H< 20 m), on peut, de manière générale, éviter l'ingestion en rehaussant la sorties d'évacuation ou en augmentant le débit. Toutefois, pour des valeurs élevées de H, ces options de conception ne seront probablement pas pratiques.

Les configurations de type B sont regroupées suivant que S égale 0 (espace nul), que S soit inférieur à 30 m (faible distance, inférieure à la largeur typique du bâtiment élevé voisin) ou que S se situe entre 30 et 60 m. Lorsque la distance séparant les bâtiments est nulle, les valeurs de dilution près du mur sous le vent du bâtiment élevé en amont seront relativement faibles. Les valeurs minimales de dilution se rapprocheront de celles prévues par le modèle de dilution ASHRAE. Toute augmentation de la distance entre les bâtiments aura pour effet d'augmenter de manière importante les valeurs de dilution près du mur du bâtiment voisin, selon la largeur du bâtiment en amont. En ce qui a trait à un bâtiment en amont relativement étroit (W égale 30 m), les valeurs de dilution près du mur sous le vent excéderont celles prévues par la formule de dilution minimale de l'ASHRAE, même pour une distance relativement faible de 30 m. Par contre, un large bâtiment, où W égale 60 m, en amont du bâtiment émetteur demandera une plus grande distance de séparation pour obtenir des taux de dilution élevés près du mur du bâtiment voisin.

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PREAMBLE

A research project was commissioned by Canada Mortgage and Housing Corporation (CMHC) in May 2000 in order to evaluate the dispersion of pollutants from rooftop sources on high-rise buildings so that guidelines on the placement of stacks and intakes could be developed. The reingestion of building exhaust into fresh air intakes has been shown to adversely affect indoor air quality. Often the source of the contaminants is an adjacent building, which may or may not be a residential structure.

Although a number of experimental studies have investigated the dispersion of exhaust from low-rise buildings, relatively little work has been conducted concerning high-rise buildings. The purpose of this study is to provide some guidelines to building designers concerning the placement of fresh-air intakes on such buildings. The project was carried out in two phases.

The first phase of the study had two objectives:

1. conduct a literature review of previous work concerning dispersion around high-rise buildings; and

2. carry out flow visualization experiments in a water flume to identify building configurations that may produce exhaust reingestion.

The second phase of the research project consists of the collection of quantitative data for the critical building configurations identified in the initial phase of the study and the analysis of results to examine the effect of stack height and location on the dispersion of exhaust from rooftop stacks. A boundary layer wind tunnel has been used extensively for the measurements required in this portion of the study.

LITERATURE REVIEW

Contamination of fresh air entering high-rise residential buildings can occur if the exhaust plume of the building or a nearby building comes in contact with the air intake. There have been numerous incidents of air intake contamination, although such incidents have not been publicized broadly. The cost of poor placement of an exhaust vent or air intake can be significant, as Bahnfleth and Govan (1987) show for a particular case.

The ingestion of pollutants cannot be completely eliminated. However, the risk of significant intake contamination can be minimized by placing the air intakes in the optimum location. Little information is currently available to assist the building designer with the placement of fresh air intakes. Much of the previous research on dispersion of plumes near buildings is based on wind tunnel studies performed with isolated buildings. A need exists to develop simple guidelines for predicting the influence of nearby buildings on the behavior of plumes emitted from rooftop stacks.

One of the causes of poor indoor air quality at high-rise residential buildings is the sporadic ingestion of contaminated air at fresh air intakes. Unfortunately, the state-of-the-art has not been sufficiently advanced to allow building engineers to apply appropriate design criteria to avoid this problem for new construction or to help alleviate it for existing buildings. Dispersion models currently used by building designers are based largely on results obtained with isolated, low-rise buildings. Little information is available concerning the risk of air intake contamination for high-rise buildings in close proximity to other buildings of similar height. As noted in ASHRAE (1999), *"large buildings, structures and terrain close to the emitting building can have adverse effects on dilution of stack exhaust because the emitting building can be within the recirculation flow zones downwind of these nearby flow obstacles."* Such incidents occur but are only rarely publicized.

A limited amount of research has previously been carried out on the subject of plume dispersion near high-rise buildings, which, in the present context, include buildings 10 to 30 storeys high. Wilson (1976) measured concentration distributions on the roof and walls of models of low-rise and high-rise buildings in a wind tunnel. The results show that vent location and building shape can have a significant influence on maximum concentration. However, the results are of limited use to building designers because the exhaust momentum ratio, M, was quite low (<1), where M is defined as the ratio of exhaust speed to wind speed. Furthermore, the experiments were performed with isolated buildings with flush vents.

In a subsequent water channel study, Wilson (1979) evaluated the size of the recirculation zone that forms on the roof of the buildings. This is important for the design of building exhaust systems since stacks should be located outside this zone. Based on experiments with a large number of building shapes, the following expression for the recirculation length scale, R, was obtained:

$$R = \left(D_{small}^{0.67}\right)\left(D_{large}^{0.33}\right)$$

where D_{large} is the largest dimension of the upwind face of the building and D_{small} is the smallest dimension of the upwind face.

The length of the separated flow region on the roof at the leading edge of the building can be expressed as a function of R such that:

$$L_c = 0.9\ R$$

These formulas only apply for the case of a wind that is approximately normal to a building wall, which is considered to be the critical case. However, for wind directions of 30-60 degrees, delta-wing type conical vortices form along the leading edges of the roof.

Although numerous studies have evaluated plume dispersion from rooftop sources, most of these studies have dealt with low-rise structures, e.g. Wilson and Chui (1985,1987), Li and Meroney (1983). Furthermore, most previous fundamental studies have investigated plume behavior for isolated buildings [see Wilson et al. (1998)]. Studies of wind loads on buildings have shown that adjacent buildings can significantly affect the flow patterns around a high-rise structure. Wilson et al. (1998) have shown that plumes emitted from a low-rise building can be significantly affected by an upwind adjacent building. If the emitting building is upwind of a taller building, the plume will impinge on the tall building, possibly leading to contamination of the fresh air intakes.

Current design standards recommend that stacks have high exit velocities to alleviate the problem of exhaust reingestion at fresh air intakes of buildings. They also refer to the ASHRAE minimum dilution formulas [ASHRAE (1999)]. However, case studies performed by a number of researchers have shown that, even with high exit velocities, pollutant concentrations may be unacceptably high at particular locations [Stathopoulos et al. (1999), Georgakis et al. (1995), Wilson and Lamb (1994)]. Several factors may account for the occasional poor performance of such stacks. These factors include the location of the stack relative to regions of flow separation and flow re-attachment, the height of the stack (h_s) and the occurrence of high upstream turbulence.

A number of semi-empirical models exist for the evaluation of minimum dilution ($D_{min}=C_e/C_{max}$) of exhaust from rooftop stacks, where C_e is the exhaust concentration and C_{max} is the maximum concentration at a receptor for a particular wind speed. One of the most widely-used models was developed by Wilson and Chui (1985) and later revised by Wilson and Lamb (1994). In this model, which is recommended by ASHRAE (1999), minimum dilution along the plume center-line is given by:

$$D_{min} = (D_o^{0.5} + D_d^{0.5})^2 \qquad (1)$$

where D_o is the initial dilution due to ambient air entrainment at the exhaust location and D_d is the distance dilution which is produced by atmospheric and building-generated turbulence. The formulas for D_o and D_d are:

$$D_o = 1 + 13M \qquad (2)$$

$$D_d = B_1 S^2/MA_e \qquad (3)$$

where B_1 is the distance dilution parameter, S is the distance from the source, A_e is the exhaust area and M is the ratio of exhaust gas velocity, w_e, to wind speed at the building height, U_h.

The minimum dilution model given by Equations 1-3 is applicable for flush vents, which generally produce low dilution at nearby receptors. As stack height increases, dilution at roof level near the stack tends to increase. On the other hand, a tall stack will tend to produce lower dilutions than a flush vent at receptors located some distance away from the stack. ASHRAE (1999) provides formulas for estimating the influence of stack height on dilution values.

Wind tunnel results obtained by Wilson and Chui (1987) have shown that B_1 may be affected by a number of factors, including building shape, wind direction and atmospheric turbulence. The ASHRAE (1999) model takes into account the effect of upstream turbulence using the following formula for B_1:

$$B_1 = 0.027 + 0.0021\sigma_\theta \qquad (4)$$

where σ_θ is the standard deviation of wind direction fluctuations in degrees and varies between 0° and 30°.

The Wilson/Chui/Lamb model does not consider the influence of building geometry, although ASHRAE (1999) recommends that B_1 should be small for isolated high-rise structures due to low turbulence levels at roof level. For building heights greater than 90 m, it is recommended that $\sigma_\theta = 0$, giving $B_1 = 0.027$. This value of B_1 may reduce predicted dilution (increase predicted concentration) by 30% or more, compared to that for a low-rise building in an urban environment. Note that this recommendation only applies for an **isolated** high-rise building. If surrounding buildings are similar in height or higher than the building of interest, turbulence will be high at roof level and consequently, dilution values are expected to be higher than those for an isolated building.

The ASHRAE (1999) model was derived from wind tunnel experiments for which the emission source and the receptors were on the roof. Li and Meroney (1983) have shown that dilution measured at wall receptors is significantly larger than at a rooftop receptor that is located the same distance away from the source. Thus, it is generally preferable to locate fresh air intakes on the upper walls of a building when emission sources are on the roof. ASHRAE (1999) recommends that the first term of Equation 4 should be increased from 0.027 to 0.10 for wall receptors, to account for the absence of direct contact of the plume at these locations. This increase in B_1 will result in an increase of 30% to 50% in predicted minimum dilution, depending on the distance from the stack to the receptor.

Kukadia and Palmer (1996) compared concentrations of various external pollutants in an air-conditioned (AC) building with those measured in an adjacent building that was naturally ventilated. The buildings were located in a large urban centre in the U.K. The study found that contaminant levels were generally similar in the two buildings. The air-conditioned building usually had lower pollutant concentrations than the naturally ventilated building. However, boiler emissions from the AC building were occasionally entrained into the fresh air intake. Figure 1 shows a one-week record of nitrogen dioxide (NO_2) concentration measured in the two buildings. Also shown is the concentration of NO_2 measured outside the buildings. Although the records are limited in duration, they clearly show that the indoor concentration correlates well with the exterior concentration. However, the buildings tend to filter out short duration peak values present in the external time series. It is also apparent that the air-conditioned building is subject to occasional very high concentrations due to reingestion at its fresh air intake. In this particular instance, high NO_2 concentration was recorded for several hours when the plume from a rooftop boiler made contact with the air intake.

The placement of fresh air intakes has recently been investigated by Rock and Moylan (1999). They note that *"more research is needed on ventilation intake placement for common commercial HVAC systems with rooftop, through-the–wall and at-grade louvers. Most existing knowledge is derived from the many studies on industrial stack exhaust gas reentrainment and not common HVAC geometries."* Rock and Moylan (1999) conclude that the ASHRAE Standard for ventilation (ANSI/ASHRAE 62-2001) needs to provide better design guidelines concerning the placement of fresh air intakes.

Research dealing specifically with ventilation systems in apartment buildings has been carried out by Kovanen et al. (1994). Full-scale experiments were carried out on a 3-storey apartment building to evaluate the dispersion of exhaust from a wall outlet. It was concluded that Wilson's minimum dilution model for roof exhausts is applicable to wall exhausts for distances less than 5 m. Broas (1996) carried out a similar study with three buildings. It was found that the Wilson model was conservative when the exhaust and receptor were on the same wall. However, the model was not reliable in niches and corners.

Effect of Adjacent Structures

A recent study by Wilson et al (1998) evaluated the influence of an adjacent building, either upwind or downwind, on the dispersion of exhaust from a rooftop stack. It was shown that dilution values on the roof of the emitting building may be reduced by as much as a factor of ten if a taller adjacent building is upwind. The study also showed that the width of the emitting building is important. In this case, an increase in width by a factor of two may decrease dilution by a factor of five.

Tests performed by Wilson et al (1998) with a higher adjacent building downwind of the emitting building showed that concentrations measured on the windward wall of the tall building did not vary significantly with height. The study concluded that it is difficult to develop design guidelines for the case of an emitting building lower in height than an adjacent building. Increasing the height of the stack or the exhaust velocity usually does not significantly improve dilution levels at nearby receptors for this building configuration.

Effect of Rooftop Structures

Most buildings have rooftop structures such as penthouses and mechanical rooms that can significantly influence plume behavior. For example, results of an experimental study by Schuyler and Turner (1989) indicated that an obstacle located near a stack may cause dilution values at rooftop receptors to be significantly below those predicted by the ASHRAE minimum dilution formulas.

Stathopoulos et al. (1999) carried out a series of full-scale tracer gas experiments with two buildings in downtown Montreal. Results of these tests indicated that dilution models recommended by ASHRAE (1999) are not always conservative. Furthermore, the use of high velocity exhaust stacks may not guarantee adequate plume dilution at rooftop intakes, especially if rooftop structures are present. Structures such as penthouses may cause plume downwash, depending on the wind direction.

Architectural screens placed around stacks for aesthetic purposes can also significantly reduce dilution values. Petersen et al. (1997) carried out extensive wind tunnel tests with various screen geometries and stack heights. A *stack height reduction factor (SHR)* was determined which allows adjustment of the ASHRAE minimum dilution estimates. This study also showed that the ASHRAE (1999) dilution formulas for non-zero stack height need improvement. In particular, the plume height/spread parameter specified in ASHRAE (1999) was shown to produce significant overestimation of D at locations near the stack.

Summary

Previous studies have focused largely on the dispersion of exhaust from stacks on isolated, flat-roofed buildings. Petersen et al. (2002) elaborate on ASHRAE-based design guidelines regarding exhaust and air intake systems. The influence of taller adjacent buildings has received little attention. Likewise, the effect of rooftop structures has not been studied extensively. The present study addresses the former issue –specifically, the effect of a tall building placed upwind or downwind of a smaller emitting building.

EXPERIMENTAL METHODS

Water Flume Study

A flow visualization study was carried out in a water flume to assess the dispersion of effluent from a rooftop source on a typical multi-unit residential building. The purpose of this study was to identify building configurations that may produce high pollutant concentrations on the surface of the emitting building or an adjacent building.

Based on the flow visualization results, a number of configurations were investigated in a wind tunnel study to obtain quantitative dispersion data. In particular, tests were performed with a taller adjacent building located either upwind or downwind of the emitting building.

The flow visualization experiments were carried out in the water flume of the Building Aerodynamics Laboratory of the Centre for Building Studies at Concordia University. The flume width at the test section is 0.75 m; the water depth was approximately 0.22 m. Figure 2 shows a plan view and cross-sectional view of the flume.

A suburban atmospheric boundary layer was simulated in the tests. The boundary layer was created using a roughness fetch consisting of plastic blocks (Lego). In addition, triangular spires and a fence were placed at the entrance of the channel (see Figure 2).

The vertical velocity profile, measured with a DANTEC laser doppler anemometer, is shown in Figure 3. The velocity profile can be approximated by the formula:

$$U(z) = U_{ref}(z/z_{ref})^{\alpha} \qquad (5)$$

where U(z) is mean velocity at height z and z_{ref} is the reference height. The power law exponent, α, was approximately 0.24.

The emitting building was constructed using plastic blocks with a side dimension (W) of 31 mm. Most experiments were carried out using a square-shaped building with a height of 57 mm. Assuming a model scale of 1:1000, the model represents a building 31 m wide 57 m high. At a scale of 1:1000, the model represents a building with approximately 15 storeys. However, the results may be assumed to be relatively insensitive to model scale, following Wilson and Chui (1994).

Experiments were also carried out for adjacent model widths of 2W and 4W. Figure 4 shows the various configurations that were tested.

The square-shaped model had a single, centrally-located exhaust outlet which was flush with the roof surface. The outlet diameter was 1.6 mm. The plume was visualized using dye with neutral buoyancy. Most tests were carried out with an exhaust momentum ratio, M = 2; thus, the exhaust speed, w_s was approximately twice the velocity of the channel flow measured at the building height (U_h). For typical stacks, M-values will vary between 1 and 6, depending on the wind speed; M=2 represents moderate to strong wind conditions, which tend to produce the most critical situation for design.

The flow speed at the building height was 0.26 m/s. This value of U_h gave a building Reynolds number ($Re_b = U_hW/\nu$) of approximately 7000, where ν is the kinematic viscosity of water. This value does not meet the strict criterion for Reynolds number independence, Re_b = 11,000, specified in ASHRAE (2001). However, Castro and Robins (1977) have shown that in a turbulent boundary layer, the flow around a sharp-edged building is insensitive to Reynolds number for $Re_b > 4000$.

Another parameter that may influence the results is the stack Reynolds number ($Re_s = w_sd_s/\nu$), where d_s is the outlet diameter. The value of Re_s in the present study, assuming an M-value of 2, was approximately 700, which is significantly below the critical value to provide turbulent exhaust flow (Re_s = 2000). Although the lack of turbulent exhaust flow may have influenced the plume behavior to some extent, this effect probably becomes less significant as distance from the outlet increases. Wilson et al (1998) suggest that, for a laminar model exhaust flow, the M-value should be adjusted by a factor of 1.41 to obtain an equivalent full-scale M-value.

Wind Tunnel Study

Tracer gas experiments were carried out in the boundary layer wind tunnel of the Building Aerodynamics Laboratory. The working section of the tunnel is 12.2 m long and 1.8 m wide. The tunnel has an adjustable roof height to provide a negligible pressure gradient in the downstream direction. The average height of the working section is approximately 1.6 m. The wind speed at the reference height (z = 600 mm) was approximately 6.6 m/s.

The wind tunnel experiments were conducted using a suburban exposure, which was simulated at a scale of approximately 1:400. Vertical profiles of mean wind speed and turbulence intensity are shown in Figure 5.

The configurations tested in the wind tunnel were similar to those used in the water flume. Most tests were performed with a taller adjacent building located either upwind or downwind of the emitting building. For comparison purposes, experiments were also performed with an isolated emitting building. A photograph showing a typical configuration is shown in Figure 6.

The emitting building was a rectangular prism with a square plan-form. The height (H), width (W) and length (L) of the model were 135 mm, 75 mm and 75 mm, respectively. At a scale of 1:400, the model corresponds to a full-scale building with a height of 54 m and a width/length of 30 m.

The adjacent building varied in size, but was always taller than the emitting building. The height and width of the adjacent building will be denoted in this report as H_a and W_a, respectively. Tests were carried out for H_a =1.3H, 1.7H and 2.0H and for W_a = W and 2W.

The tracer gas, sulfur hexafluoride (SF_6), was emitted from a flush vent on the roof of the model or from stacks of different heights. Different vent locations were used during the study, as shown in Figure 7. Each vent was 4 mm in diameter, which corresponds to a full-scale diameter of 1.6 m.

Air samples were obtained at an array of receptors located on the nearest wall of the adjacent building. A typical distribution of receptors is shown in Figure 8 for the buildings with the same width as the emitting building. Samples were also obtained along the vertical center-line of the leeward wall of the emitting building.

Samples were collected via plastic tubes (1.6 mm i.d.) attached to the walls of the models. A multi-port syringe sampling system was used to obtain air samples at up to 10 locations simultaneously. The sampling time was 1 minute, which corresponds to a full-scale averaging time of 5 to 10 minutes. Mean concentrations of SF_6 were evaluated by injecting a portion of the sampled volume into a VARIAN gas chromatograph. Several injections were performed for each sample to ensure that contamination from the previous sample did not occur.

Most tests were performed for M=2. For typical stacks, this exhaust momentum ratio is associated with moderately strong winds for which plume rise will be minimal. Thus, the experimental results should be representative of critical conditions with respect to the potential for exhaust reingestion at fresh air intakes.

FLOW VISUALIZATION RESULTS

Water flume experiments were initially carried out using an isolated building model. Two wind directions were evaluated, namely $\theta=0°$ and $\theta=45°$.

Figure 9 shows a plume emitted from the square-shaped building for $\theta=0°$. The photograph was taken with a digital camera using an exposure time of 0.25 s. The photo indicates that for this building shape and wind direction, the plume does not make contact with the building surfaces when M=2.

Significant changes to the plume behavior are evident when a tall building is located either upwind or downwind of the emitting building. Figure 10 shows that plume rise is significantly reduced when a building with height 2H and width W is located downwind of the emitting building. Although most of the plume is carried downwind, the photo indicates that large pollutant concentrations may occur at a fresh air intake located near the top of the leeward wall of the emitting building. Intakes on the downwind building would also be affected if they are located at approximately the same height as the upstream building. Note that the separation distance between buildings, which was approximately 0.8W in this case, is an important parameter. The configuration shown represents two buildings on opposite sides of a street.

The plume shown in Figure 10 clearly travels around the downwind building. However, if the width of this building is increased, more of the plume will be trapped in the gap between the buildings. This situation will produce large pollutant concentrations at all levels below the roof of the emitting building.

Figure 11 shows a tall building located approximately 0.25W upwind of the emitting building for $\theta=0°$. This situation, which corresponds to two buildings separated by an alley, produces relatively large plume rise due to the sheltering effect of the upwind building. Consequently, pollutant concentrations on surfaces of the emitting building are very small. On the other hand, the plume is drawn to the upper portion of the tall building due to the presence of negative pressure on the leeward surface of this building. This indicates that a wall intake located near the roof of the tall building would experience significant contamination.

Similar results were obtained with a tall upwind building for $\theta=45°$, as shown in Figure 12. This configuration produced significant upwind transport of the plume. Depending on the exhaust constituents, this situation could result in indoor air quality problems for the upwind building.

WIND TUNNEL RESULTS

Based on the results of the flow visualization experiments, various model configurations were chosen for tracer gas experiments in the wind tunnel. Tests were performed using the following basic configurations:

1. isolated building with a central flush stack
2. emitting building upwind of a taller building
3. emitting building downwind of a taller building.

In each case, tracer gas concentrations were obtained at wall receptors since fresh air intakes are generally located on vertical surfaces.

The effects of various parameters were investigated. These included the width and height of the adjacent building, and separation distance between buildings. For some configurations, additional tests were performed to determine the significance of M-value, wind direction, stack location and stack height.

Evaluation Criterion

High-rise residential structures may be near a research lab or a hospital, each of which could be a source of toxic chemicals or hazardous biological emissions. Odorous sources, such as diesel and kitchen exhaust may also be a problem. Because of the wide variety of pollutants that may be emitted from rooftop stacks it is not possible to specify a critical dilution value that should be exceeded in practice. The critical dilution will vary depending on the type of source.

In the present study, wind tunnel results were evaluated by comparing minimum dilution measurements with D_{min} values obtained with the Wilson/Chui/Lamb model (Equations 1-4), which is currently recommended by ASHRAE (1999). It should be noted that the ASHRAE D_{min} model is intended to provide conservative estimates of dilution at a given receptor location (e.g. air intake, window etc.).

The purpose of the present study is to identify building configurations that have a high risk of reingestion of exhaust at fresh air intakes, and in particular, to identify those configurations for which the ASHRAE D_{min} model is unconservative. These configurations should be avoided when nearby exhaust sources produce significant amounts of toxic or odourous gases, or else mitigating measures should be performed to reduce the likelihood of air quality problems.

Isolated Building

The isolated building was tested for a wind angle of 0° with a flush stack located in the center of the roof with the M-value set at 2.0. For a stack with a typical exhaust speed of 12 m/s, this M-value corresponds to a moderately strong wind speed of 6 m/s.

The dilution profile measured on the leeward wall of the isolated building will be used as a reference to evaluate the influence of adjacent building in the following sections of the report. The choice of M=2 is expected to produce near-critical dilution values at near-field receptors tend to occur for moderate M-values. At a given distance from the source, dilution on the plume center-line will depend on wind speed. At each receptor, there exists a critical M-value (wind speed) that produces the critical dilution [ASHRAE (1999)]. At high M-values (low U_h), plume rise will be large and consequently, dilution at leeward wall receptors will be high. Likewise, low M values (high U_h), are not expected to produce the critical dilution since high wind speeds tend to increase plume dilution. Furthermore, it should be noted that low M-values are relatively rare since high wind speeds have a low probability of occurrence.

Figure 13 shows the vertical distribution of dilution on the leeward wall for the isolated building. The minimum dilution is approximately 400 and occurs near the top of the wall. Dilution increases significantly as receptor height decreases – reaching a value of 1000 at z=0.7H. Dilution continues to increase marginally as height decreases. The maximum dilution is approximately 1600 near ground level.

Also shown in Figure 13 is the minimum dilution curve obtained with the Wilson/Lamb model recommended in ASHRAE (1999). The distance dilution parameter, B_1, was set at 0.132, which is the recommended value for hidden receptors on a vertical wall. In this case, the measured dilution values are at least five times larger than the ASHRAE D_{min} values. Thus, the use of the ASHRAE model would result in a highly conservative design for an isolated building.

Emitting Building Upwind of a Taller Adjacent Building

A number of experiments were performed with the emitting building upwind of a taller building. With this configuration, maximum concentrations occur on the windward wall of the adjacent building. The following parameters were investigated:

Height of adjacent building (H_a =1.3H, H_a=2H)

Width of adjacent building (W_a=W, W_a=2W)

Building separation (S=0, S=W, S=2W)

Tracer gas concentrations were measured on the leeward wall of the emitting building and the windward wall of the adjacent building since either (or both) of the buildings could be a high-rise residential building. The results may be useful for estimating dilution values at wall intakes or windows. The results may also be applicable for intakes located on the wall of a penthouse of the adjacent or emitting building, depending on the size and orientation of the penthouse.

For some high-rise residential structures, the air intake is contained in a packaged rooftop unit. Saathoff et al. (2002) have shown that such rooftop structures on an emitting building can significantly affect plume behavior. The present study has considered only a flat-roofed emitting building. This implicitly assumes that the stack is situated at the highest roof level, away from the influence of any rooftop structures.

The measurements were obtained along the center-line of the models – the line of maximum concentration. Thus, the dilution profiles that follow show the minimum dilution at each height.

Minimum dilution on adjacent building

Figure 14 shows vertical distributions of dilution measured along the center-line of the windward wall of the single-width adjacent building (W_a=W) for H_a=1.3H. Data are shown for no gap between buildings (S=0) and for gaps of W and 2W. Also shown are curves obtained with the ASHRAE D_{min} model.

Dilution values obtained for S=0 are significantly lower than those obtained when a gap between buildings exists. The minimum dilution obtained with S=0 is approximately 70, whereas D_{min} increases to approximately 300 for S=W and 500 for S=2W. The increase in D_{min} with S is partly associated with the increase in distance from source to receptor. The effect of distance on dilution is indicated by the change in ASHRAE dilution values for different gap sizes. However, the large increase in measured dilution for S=W compared to data obtained for S=0 indicates that the plume characteristics may be altered when a gap is introduced. The additional increase in dilution in this case may be due to enhanced plume spread associated with a flow instability at the windward wall of the adjacent building. The influence of such an instability on plume behavior will depend on a number of factors such as the relative heights of the two buildings, plume height, and the geometry of the adjacent building.

The minimum dilution on the 1.3H adjacent building occurs near the top of the wall, since the plume is in a flow region where the streamlines have an upward trajectory. The location of minimum dilution could be problematic in this case since fresh air intakes are usually located near roof level.

In each case (S=0, S=W and S=2W), the measured D_{min} values are larger than those predicted by the ASHRAE model. For S=0, the discrepancy is relatively small. However, for S=W and S=2W, the data exceed the predicted values by at least a factor of 2. Thus, the ASHRAE model is conservative in this case and is appropriate for design purposes.

Data obtained with the tall adjacent building (H_a=2H) are shown in Figure 15 for S=0, S=W and S=2W. Note the difference in shape of the dilution profiles for the 2H model, compared to those for the 1.3H model, shown in Figure 14. For each S value, the minimum dilution occurs at the lowest measurement height, rather than near the roof, due to the bifurcation of the flow on the windward face of the adjacent building. Previous studies have shown that this bifurcation occurs at a height $z=0.67H_a$. The plume in this case is emitted at $z=0.5H_a$ and, since plume rise is small, it is transported downward. (see flow visualization result in Figure 10). Dilution values at roof level are more than a factor of 10 larger than those measured at the lowest height, indicating that only a small portion of the plume reaches the upper part of the wall. Consequently, when the downwind building is significantly taller than the emitting building, the risk of significant contamination of upper-level fresh air intakes is small since most of the plume is transported downward.

As with the 1.3H adjacent building, dilution values obtained for S=0 are significantly lower than those obtained when a gap between buildings exists. The minimum dilution obtained with S=0 is approximately 60, whereas D_{min} increases to approximately 500 for S=W and 1000 for S=2W.

The ASHRAE D_{min} curves are also shown in Figure 15. As with the smaller adjacent building, the measured D_{min} values are larger than the predicted values for each value of S. For S=0, the discrepancy between measured and predicted dilution is relatively small near the roof of the emitting building, with the measured dilution only 20% larger than the ASHRAE value. However, in this case, the measured dilution increases rapidly with height and is approximately 10 times larger than the ASHRAE value at the roof level of the adjacent building.

Minimum dilution on emitting building

Figure 16 shows the dilution distribution measured on the leeward wall of the upwind emitting building for S=W and S=2W for both the 1.3H and 2H adjacent building. Data are also shown for the isolated building for comparison purposes.

The results show little effect of height of adjacent building. Dilution values obtained with the 1.3H building downwind of the emitting building are slightly larger than values obtained with the tall building at most receptors. The major factor affecting dilution is the distance between buildings. For S=2W, D values are approximately 3 times greater than those for S=W.

Figure 16 highlights two important findings. First, the addition of a taller building downwind of the emitting building reduces dilution (increases concentrations) on the entire leeward wall of the emitting building compared to values obtained with an isolated building. The magnitude of dilution reduction depends on the separation distance. As S decreases, dilution decreases at all points on the windward wall of the adjacent building. The results suggest that the effect of the adjacent building is small for S>2W.

Secondly, the results indicate that the ASHRAE D_{min} model is generally conservative for receptors on the leeward wall of the emitting building. However, for the smallest separation (S=W), the model was not conservative for receptors near ground level. Thus, for very small separations (the size of an alley, for example), the ASHRAE model may not be applicable.

Experiments were repeated for a double-width building placed downwind of the emitting building. Dilution profiles were similar to those obtained with the single-width building. In general, dilution values at most receptors were slightly larger with the double-width building.

Upwind emitting building [Wilson et al. (1998)]

The influence of an adjacent building on plume dispersion has been investigated by Wilson et al. (1998) using a water flume. However, in this previous study, the emitting building was a low-rise structure with a full-scale height (H) of only 12 m and the adjacent building height varied from 0.5H to 2H. Thus, the results of Wilson et al. (1998) are not directly applicable to high-rise residential buildings. However, comparison of these data with the present results demonstrates the influence of building height and plume rise on the dilution profiles.

Figure 17 shows results of the two studies for the emitting building upwind of a taller adjacent building (H_a=2H). Dilution profiles on the windward wall of the adjacent building are shown for the case of no gap between buildings (S=0). Also shown are predicted dilutions obtained with the ASHRAE D_{min} model. The M value was approximately 2 and the stack was located at the center of the roof. It should be noted that the data of Wilson et al. were obtained with a 2.1 m tall stack.

The measured dilution profiles obtained in the two studies are not similar. In the present study, the minimum dilution occurred at a height, z=H, i.e. at the base of the adjacent wall. On the other hand, Wilson et al. (1998) obtained the minimum dilution near the top of the adjacent wall (z=2H). This discrepancy is mainly a result of the difference in building heights used in the two studies.

The stack height used by Wilson et al. was different from that used in the present study. However, this should not be a significant factor. In the present study, the stagnation point on the windward face of the adjacent building was located at approximately $z=2/3H_a$, at a full-scale height 18m above the emitting building roof. Below this height, the flow is downward along the windward face.

In the present study, the plume rise, h_r, is estimated to be 9.6 m, as determined using the following formula [Briggs (1984)]:

$$h_r = 3Md_s \qquad (6)$$

with M=2 and d_s=1.6 m. If a 2 m stack had been used in the present study, the plume height would have been approximately 12 m – still well below the stagnation point. Consequently, it can be concluded that the plume behavior would not be significantly different if a 2 m stack were used in the present study.

In the Wilson study, the plume rise obtained from Equation 6 (M=2, d_s=0.6 m) was 3.7 m. Thus, with a stack height of 2.1 m, the plume height was 5.8 m above the emitting building roof. Assuming the stagnation point on the adjacent building wall was approximately 4 m above the roof, the plume would usually contact the adjacent building near its roof. The dilution data shown in Figure 17a seem to verify this, although the relatively constant D values on the windward face indicate that the plume spends a significant portion of time below the stagnation point in this case.

Emitting Building Downwind of a Taller Adjacent Building

Wind tunnel experiments were performed with the emitting building downwind of a taller building. Parameters investigated include:

Adjacent building height (H_a =1.3H, H_a=1.7H, H_a=2H)

Adjacent building width (W_a=W, W_a=2W)

Building separation (S=0, S=W, S=2W)

Wind direction (θ=0°, θ=45°)

Stack location (center, upwind edge, downwind edge, corner)

Unlike the previous configuration (upwind emitting building), dilution values were measured only on the leeward wall of the adjacent building. Flow visualization experiments have shown that the highest concentrations will occur on the adjacent building wall when the lower emitting building is downwind (see Figures 11 and 12).

It should be noted that the exhaust momentum ratio, M, is based on the reference wind speed measured at the height of the emitting building upwind of the buildings. This definition is somewhat misleading for the case of the emitting building downwind of a taller building, since the local wind speed at the stack location will be much lower than the reference wind speed due to the sheltering effect. The presence of the upwind building causes plume rise to be relatively large, even for small M. Nevertheless, this definition of M was used to allow comparison with the various configurations with an upwind emitting building.

Single-width adjacent building

Figure 18 shows vertical distributions of dilution measured along the center-line of the leeward wall of the single-width adjacent building (W_a=W) for H_a=1.3H and M=2. Data are shown for only two separation distances, S=0 and S=W. For larger separation distances, dilution values were extremely high for the 1.3H adjacent building.

The results indicate that when no gap exists between the buildings, the plume travels upwind and makes contact with the adjacent building wall. The lowest measured dilution was approximately 25 and occurred near the top of the adjacent building. Dilution increased to a value of 75 at the height of the emitting building. The measured values for S=0 are similar in magnitude to those predicted by the ASHRAE D_{min} model. The model appears to be unconservative for locations near the roof of the adjacent building.

When the two buildings are separated by a gap equal to the width of the emitting building, (S=W), dilution far exceeds 10,000 at all points on the adjacent building wall. This indicates that the plume mainly travels downwind. The low height of the adjacent building in this case produced a relatively small wake and consequently, the plume was usually outside the recirculation zone of the upwind building.

Dilution profiles obtained with the tall upwind building (H_a=2H) are shown in Figure 19. The data were obtained along the center-line of the leeward wall of the single-width building for separation distances: S=0, S=W, and S=2W.

Results obtained for S=0 were similar to those obtained with the shorter adjacent building. The plume travels upwind and makes contact with the adjacent building wall. The lowest measured dilution was approximately 50 and this occurred near the base of the wall, at approximately 0.1H above the roof of the emitting building. Dilution increased to a value of 100 approximately near the roof of the adjacent building. The measured values for S=0 are similar in magnitude to those predicted by the ASHRAE D_{min} model.

When S was increased to one building width, dilution increased significantly on the leeward wall of the adjacent building. Lowest dilution values of the order of 1000 were measured on the upper half of the adjacent building. At lower levels, D increases to nearly 10,000. The measured dilution values were significantly larger, by at least a factor of 5, than those predicted by the ASHRAE D_{min} model. The overprediction of D_{min} indicates that the plume path is usually downwind, although occasional upwind excursions may occur.

For S=2W, dilution values on the leeward wall of the 2H adjacent building were very large – in excess of 40,000 at all locations. Thus, for the single-width building located upwind of a shorter emitting building, the risk of intake contamination is low for S>W.

Double-width adjacent building

Figure 20 shows vertical distributions of dilution measured along the center-line of the leeward wall of the **double-width** adjacent building (W_a=2W) for H_a=1.3H. The results are similar to data obtained with the single-width building shown in Figure 18. However, some influence of width of the adjacent building is apparent.

For the 1.3H adjacent building with no gap (S=0), the measured dilution was approximately twice as large as that obtained with the single width building. This is probably due to an increase in lateral spreading of the plume for the double-width building. In this case, the ASHRAE D_{min} model produces conservative estimates of dilution.

As previously shown for the single-width building, increasing S caused a significant increase in dilution on the adjacent building wall. However, the increase in dilution with S was much smaller for the double-width building. For example, for S=W, dilution near the top of the double-width adjacent building wall approached 500. On the other hand, at the same location on the single-width building, dilution was approximately 25000. The relatively low dilution obtained with the double-width adjacent building for S=W indicates that the plume is effectively trapped in the near wake of the building. Thus, the wake of the double-width building is significantly larger than that of the single-width building.

The influence of crosswind dimension on wake length of a square prism is shown in Figure 21. Streamline patterns, obtained by Snyder and Lawson (1994) in a wind tunnel study, show that increasing the crosswind dimension, L, produces the following effects:

1. an increase in the streamwise length of the wake
2. an increase in the height of the wake

For example, increasing L from W to 2W produces a 30% increase in wake length and a 10% increase in wake height for this geometry. This diagram indicates that the risk of reingestion at leeside receptors is higher for wide buildings than for narrow buildings since, in the former case, plumes from sources that are relatively far downwind can be trapped in the wake.

Results obtained with the tall (H_a=2H) double-width building, shown in Figure 22, were similar to those obtained with the shorter building. However, the larger wake of the tall building caused significant reduction in dilution for S=W and S=2W. For S=W, the minimum dilution decreased by a factor of 5, compared with the single-width building. At the largest separation, S=2W, the minimum dilution was approximately 500, which is an order of magnitude less than that obtained with the short double-width building.

For S=0 and S=W, the measured dilution values on the upper wall of the **double-width** adjacent building are similar to D_{min} estimates obtained with the ASHRAE model. Recall that this was true only for S=0 for the single-width building, as shown in Figure 19. This indicates that the plume makes almost direct contact with the wall in these cases. For larger building separation (S=2W), the ASHRAE model underestimates D_{min} at all heights, indicating that the plume makes only intermittent upwind excursions in this case.

Downwind emitting building [Wilson et al. (1998)]

Wilson et al. (1998) carried out experiments in a water flume to investigate the behavior of a plume emitted from a building downwind of another building. As discussed previously, the results of this study are not directly applicable to high-rise residential buildings, since the emitting building had a full-scale height (H) of only 12 m. Nevertheless, it is useful to compare data of Wilson et al. with the present results to show the influence of building height on the dilution profiles.

Figure 23 shows results of the two studies for the case of the emitting building downwind of a taller adjacent building (H_a=2H). Dilution profiles on the leeward wall of the adjacent building are shown for the critical case of no gap between buildings (S=0). Also shown are predicted dilutions obtained with the ASHRAE D_{min} model. The M value was approximately 2 and the stack was located at the center of the roof. The data of Wilson et al. were obtained with a 2.1 m tall stack; a flush vent was used in the present study.

The measured dilution profile obtained by Wilson et al. shows that dilution was relatively constant on the leeward wall of the taller building, although D increased by 50% near the top of the wall. The dilution values exceed the ASHRAE D_{min} values by a factor of 2.5.

Results obtained in the present study, on the other hand, correspond very well with the ASHRAE model curve. A minimum dilution of approximately 50 occurred near the base of the wall, although at the lowest point, D increased to a value of 110.

The discrepancy between the measured dilution profile obtained in the present study with that of Wilson et al. is probably due to the larger height of the adjacent building in the present study relative to the plume height. For a downwind emitting building, plume rise is unpredictable since the plume is sheltered from the oncoming wind. Nevertheless, it can be conjectured that plume rise for this configuration should be larger than that given by Equation 6. The relatively high dilution values of Wilson et al. shown in Figure 23 suggest that plume rise was sufficient to allow partial escape of the plume from the wake of the adjacent building. In contrast, the relatively tall adjacent building used in the present study trapped the plume in the near wake region, producing low dilution on the leeward wall. In this case, the enhanced plume rise due to the sheltering effect of the upwind building was insufficient to allow the plume to escape the wake region, even intermittently.

For this configuration, stack location can be important, depending on the relative heights of the two buildings. Figure 24 shows results of Wilson et al. obtained with a stack close to the leeward wall of the adjacent building. In this case, the plume was trapped in the wake of the adjacent building and was carried upwind. As a result, very low dilution values were obtained near the top of the adjacent wall. The minimum dilution was approximately 50% of the ASHRAE model value at this location.

EFFECT OF STACK HEIGHT

Wind tunnel experiments were carried out for model stack heights of 0, 2.5 mm, 7.5 mm, 12.5 mm and 25 mm. These correspond to full-scale stack heights of 0, 1 m, 3 m, 5 m and 10 m.

For an upwind adjacent building, the effect of stack height is not easily predictable since the entire stack is immersed in the adjacent building's wake. Figure 25 shows the variation of minimum dilution with stack height obtained with a single-width upwind building having a height of 1.7H. Data are shown for the center stack (A) and the near corner stack (F).

In both cases, no benefit was achieved by raising the stack to 3 m. However, for the center stack, increasing h_s from 3 m to 10 m caused D_{min} to increase by a factor of 2, while for stack F, a similar increase in stack height produced less than a 50% increase in dilution. Clearly, when the emitting building is in the near wake of a taller upwind building, increasing the height of a stack provides only marginal benefits unless the stack can be raised above the height of the upwind building.

For an upwind emitting building, the effect of stack height on minimum dilution is more predictable. In this case, the plume height for non-buoyant emissions can be estimated by adding the momentum plume rise (Equ. 6) to the stack height. In some cases, an optimum stack height can be determined. For example, if an upper level air intake is the only significant wall receptor, the stack height should be set such that the plume height is less than 2/3 the height of the adjacent building. However, if openable windows exist on the windward wall of the adjacent building, the stack should extend to near the roof level of the adjacent building.

EFFECT OF STACK LOCATION

The various stack locations used in the study are shown in Figure 7. The results presented previously were obtained with a stack located in the center of the roof. However, stack location can have a significant impact on the severity of reingestion, as shown in the previous section.

Figure 26 shows, for a given gap width, the effect of stack location on minimum dilution measured on the leeward wall of an upwind building. Results are shown for a single-width adjacent building for S=W and a double-width adjacent building for S=2W. In each case, the height of the adjacent building was 2H. Note that the D_{min} values are the lowest values obtained on the wall of the adjacent building. The data are plotted as a function of x_a/W, where x_a is the horizontal distance from the stack to the wall of the adjacent building.

The results indicate that stack location is more important in the case of a narrow upwind building than for a wide upwind building. For the narrow building, minimum dilution obtained with the most distant stacks (C, D) is approximately 10 times larger than D_{min} obtained with the stacks nearest to the wall (G, F). For the wide building, on the other hand, D_{min} obtained with stacks C and D was only a factor of 3 larger than that obtained with stacks G and F.

The results indicate that stack location becomes significant when the emitting building is only partially immersed in the near wake of the upwind structure. In this case, dilution values on the adjacent building wall will be much lower for a stack near the windward roof edge than for a stack near the leeward edge.

On the other hand, if the emitting building is completely immersed in the wake of the adjacent building or if the emitting building is upwind of the adjacent building, the effect of stack location is much less pronounced. For these cases, the variation in dilution with stack location will be almost entirely due to the effect of distance. An increase in distance from stack to receptor produces an increase in dilution, as evident in the distance dilution component of the ASHRAE D_{min} model (see Equation 3).

Regarding the lateral placement of a stack, dilution values on an upwind building will depend on the location of the stack relative to the edge of the lateral edge of the wake. The highest dilution values will tend to occur for stacks near the wake edge (e.g. stack C for the single-width adjacent building in Figure 26). When the adjacent upwind building is wider than the emitting building, the lateral placement of the stack has a negligible effect on dilution values (see results obtained with stacks C and F for the double-width adjacent building in Figure 26).

EFFECT OF WIND DIRECTION

Dilution measurements were also obtained on the leeward walls of the upwind adjacent building for a wind angle, $\theta = 45°$. Experiments were carried out for S>0.3W and for building height ratios, H_a/H, of 1.3, 1.7 and 2.0.

Minimum dilution values for $\theta = 45°$ occurred for S=0.3W and were similar to those obtained for $\theta = 0°$ and S=0. However, for the standard square-section building (W=L=30 m), the increase in dilution with S was less than that for $\theta = 0°$. This is believed to be due to the relative larger wake of the building for $\theta = 45°$ compared to that for $\theta = 0°$. In addition, building downwash probably increased the plume capture by the building wake. Previous studies [e.g. Snyder and Lawson (1994), Castro and Robins (1977)] have shown that building downwash is most severe for $\theta = 45°$.

DESIGN GUIDELINES

Configurations that could lead to significant reingestion of building exhaust and subsequent air quality problems are shown in Figure 27. These can be classified as:

A. emitting building upwind of taller adjacent building (Configurations A1 – A4)
B. emitting building downwind of taller adjacent building (Configurations B1 – B6)

Design guidelines for configurations A and B are presented in Tables 1 and 2, respectively. The guidelines describe the configurations in terms of the height difference, ΔH, and the separation distance, S, between the buildings. The rationale concerning the limits of ΔH and S are discussed below.

Configuration A: Emitting building upwind of taller adjacent building

The limit of 20 m for ΔH was chosen rather arbitrarily based on the expected range of possible plume heights for a typical building stack. Assuming a maximum stack height of 10 m and a minimum plume rise of 3 m (for the design wind speed), the effective plume height is of the order of 13 m. For buildings with a large height difference (ΔH > 20 m), the plume would travel downwards when it contacts the windward wall of the adjacent building. In this case, increasing the stack height or flow rate to increase the plume height would be impractical in most cases. On the other hand, when the height difference is small (ΔH < 20 m), plume contact with the adjacent wall, if it occurs, will be near the roof. In this case, the designer has the option to increase stack height or flow rate so that the plume will travel over the adjacent building during design wind conditions.

In terms of separation distance, Type A configurations were classified as S=0 (no gap) or S<30 m (small gap less than the building width, W). The no gap case is clearly the most problematic for an upwind emitting building. An upper limit of S=30 m for potential reingestion was chosen, even though measured dilution values were relatively high in this case. This upper limit takes into account the possibility of a stack located near the leeward edge of the emitting building. In this case, dilution values would be slightly lower than those obtained with a central stack.

Configuration B: Emitting building downwind of taller adjacent building

As with Type A configurations, a dividing limit of ΔH=20 m was chosen for Type B. In this case, plume rise is unpredictable but should be relatively large due to the sheltering effect of the upwind building. For small ΔH (< 20 m), reingestion problems may be avoided for the most part by raising the stack and/or increasing the flow rate. However, for large ΔH, these design alternatives will probably not be practical.

Type B configurations were classified as S = 0 (no gap), S < 30 m (small gap less than the typical width of an adjacent tall building) and 30 m < S < 60 m (large gap, for the case of a wide upwind building). When S= 0, reingestion of exhaust at intakes or windows on the adjacent wall is likely, regardless of the width of the upwind building. For narrow upwind buildings, a relatively small gap of 30 m produces relatively high dilution. Further benefits can be achieved in this case by moving the stack as far as possible from the adjacent building. Wide upwind buildings may experience reingestion problems even for a relatively large gap of 60 m. This is due to the significant length of the wake region formed behind wide buildings.

CONCLUSION AND RECOMMENDATIONS

The present study has investigated the influence of a tall building on a plume emitted from a shorter adjacent building. The purpose of the study was to identify those building configurations that could potentially produce significant reingestion of exhaust at air intakes. It should be noted that it is effectively impossible to totally prevent some reinjestion at air intakes. However, the severity of reingestion problems can be greatly reduced by using proper stack design and avoiding problematic building geometries.

Configurations have been evaluated by comparing measured wall dilutions with values predicted by the ASHRAE minimum dilution model. Configurations that produced dilution values significantly larger than the ASHRAE values are deemed to be acceptable. On the other hand, those configurations that produced dilutions similar in magnitude to the ASHRAE values could require some type of mitigation (e.g. tall stacks, high flow rates), depending on the contaminant.

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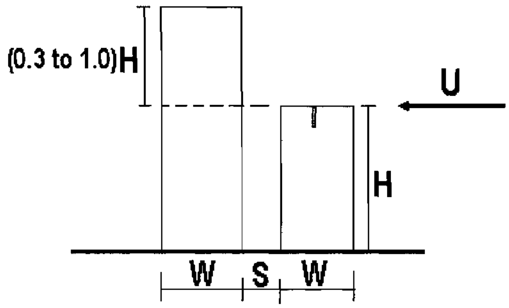
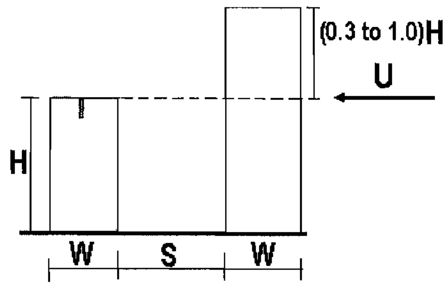
Table 1 Guidelines for an emitting building upwind of taller adjacent building



Configuration	Description	Region of plume contact	Possible mitigation measures
A1	ΔH > 20m S = 0 (no gap)	base of windward wall of adjacent building	a) openable windows should not be placed on adjacent windward wall, b) fresh air intake of adjacent building should be placed near the roof (preferably not on windward wall)
A2	ΔH < 20 m S = 0 (no gap)	windward wall of adjacent building; location of contact depends on stack height and flow rate	a) openable windows should not be placed on adjacent windward wall, b) fresh air intake should not be placed on windward wall, c) increase stack height or flow rate so that plume travels over roof
A3	ΔH > 20m) S < 30m (small gap)	base of windward wall of adjacent building; leeward wall of emitting building	a) openable windows should not be placed on adjacent windward wall or leeward wall of emitting building, b) fresh air intake of adjacent building should be placed near the roof (preferably not on windward wall), c) fresh air intake of emitting building should not be placed on leeward wall
A4	ΔH < 20m S < 30m (small gap)	windward wall of adjacent building; location of contact depends on stack height and flow rate	a) openable windows should not be placed on adjacent windward wall, b) fresh air intake should not be placed on windward wall, c) increase stack height or flow rate so that plume travels over roof

NB: Minimum plume height = $h_s + (h_r)_{min} = h_s + 4.5d$, where h_s is the stack height, d is the stack diameter and h_r is the plume rise. For small ΔH (<20 m), h_s can be set such that the plume travels above the adjacent building.

Table 2 Guidelines for an emitting building downwind of taller adjacent building



Configuration	Description	Region of plume contact	Possible mitigation measures
B1	ΔH > 20m, S = 0 (no gap)	leeward wall of adjacent building	openable windows or intakes should not be placed on adjacent leeward wall,
B2	ΔH < 20m; S = 0 (no gap)	leeward wall of adjacent building	a) openable windows or intakes should not be placed on adjacent leeward wall b) increase stack height or flow rate so that plume escapes recirculation zone behind adjacent building
B3	ΔH > 20m S < 30m (small gap)	leeward wall of adjacent building windward wall of emitting building	openable windows and intakes should not be placed on adjacent leeward wall or windward wall of emitting building;
B4	ΔH <20m S < 30 m (small gap)	leeward wall of adjacent building; location of contact depends on stack height and flow rate	a) openable windows and intakes should not be placed on adjacent leeward wall or windward wall of emitting building b) increase stack height or flow rate so that plume travels over roof
B5	ΔH > 20 m 30m < S < 60m (large gap)	Occurrence of reingestion depends on width of adjacent building W_a. For large W_a, reingestion may occur	Same as B3
B6	ΔH > 20 m 30m < S < 60m (large gap)	Occurrence of reingestion depends on width of adjacent building W_a. For large W_a, reingestion may occur	Same as B4

NB: If the upwind building is narrow, dilution values on its leeward wall can be increased by maximizing the distance between the stack and the wall.

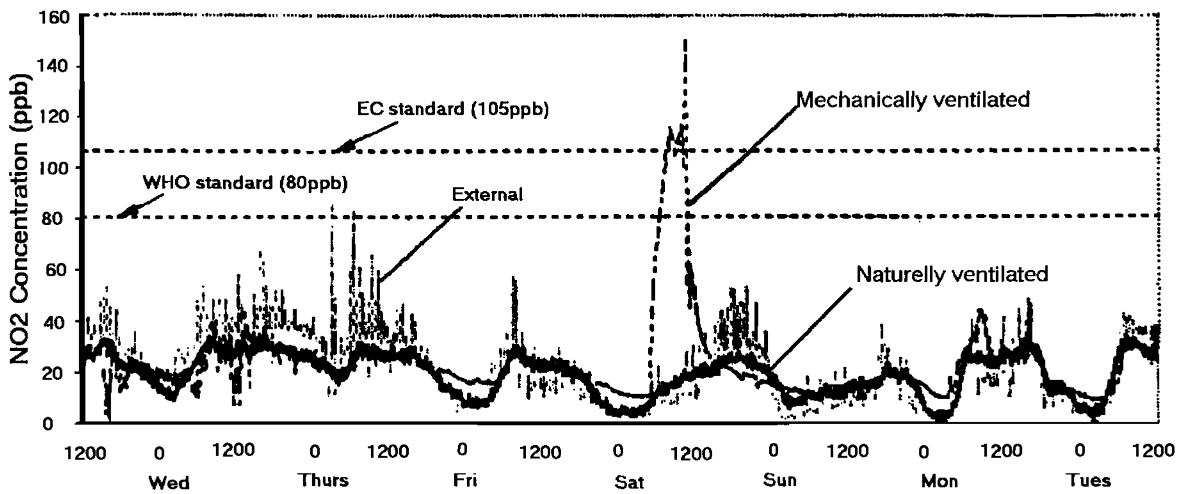


Figure 1 Time series of nitrogen dioxide concentration in two buildings in Birmingham, U.K. for the week of Feb. 13-20, 1996 [after Kukadia and Palmer (1996)]

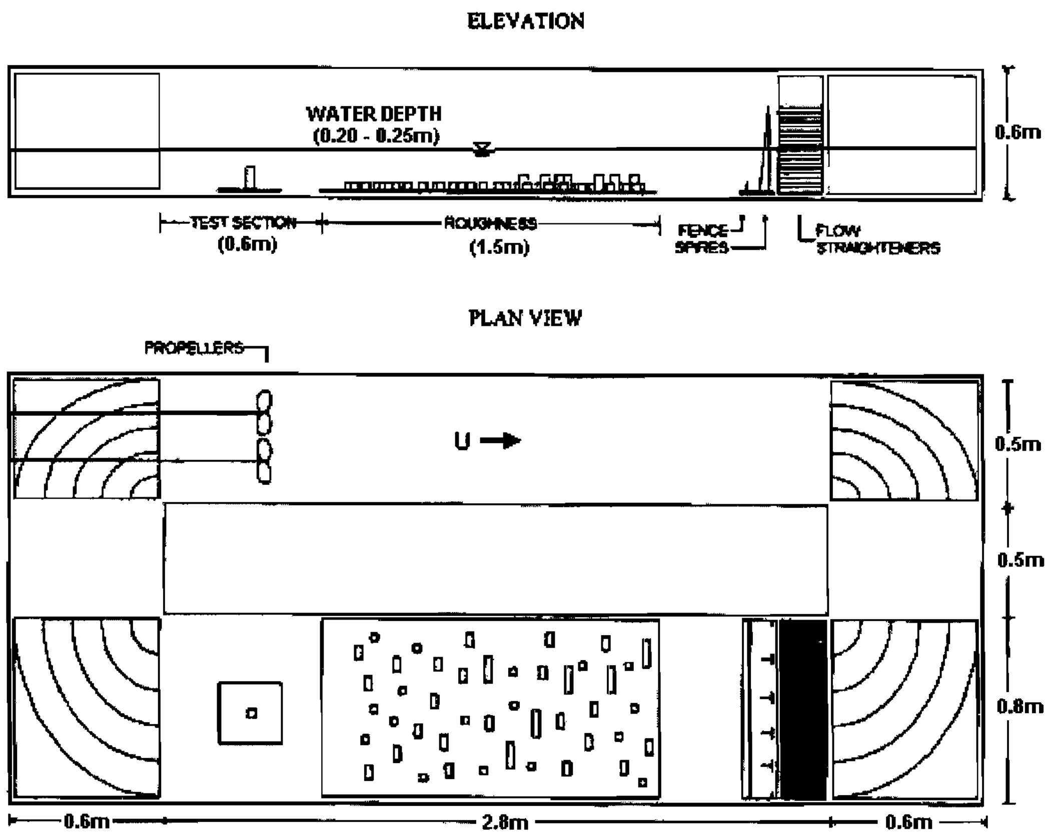


Figure 2 Plan and elevation views of the water flume

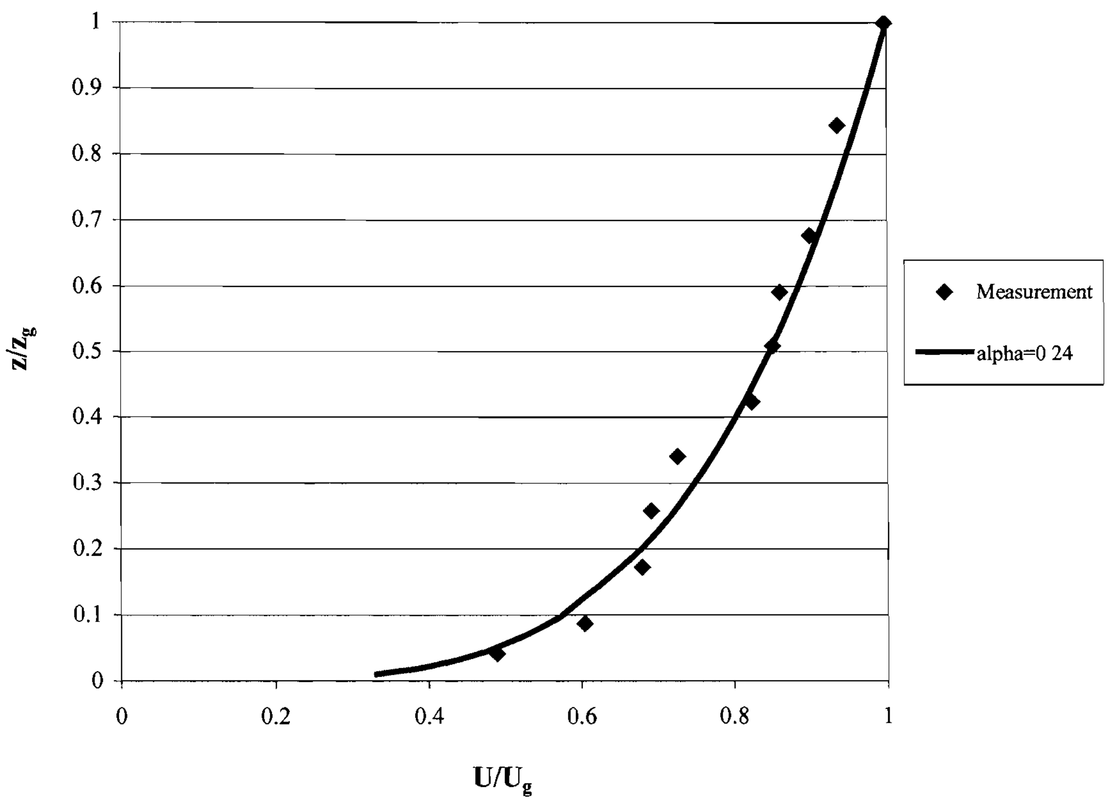


Figure 3 Mean velocity profile in the water flume at the model location

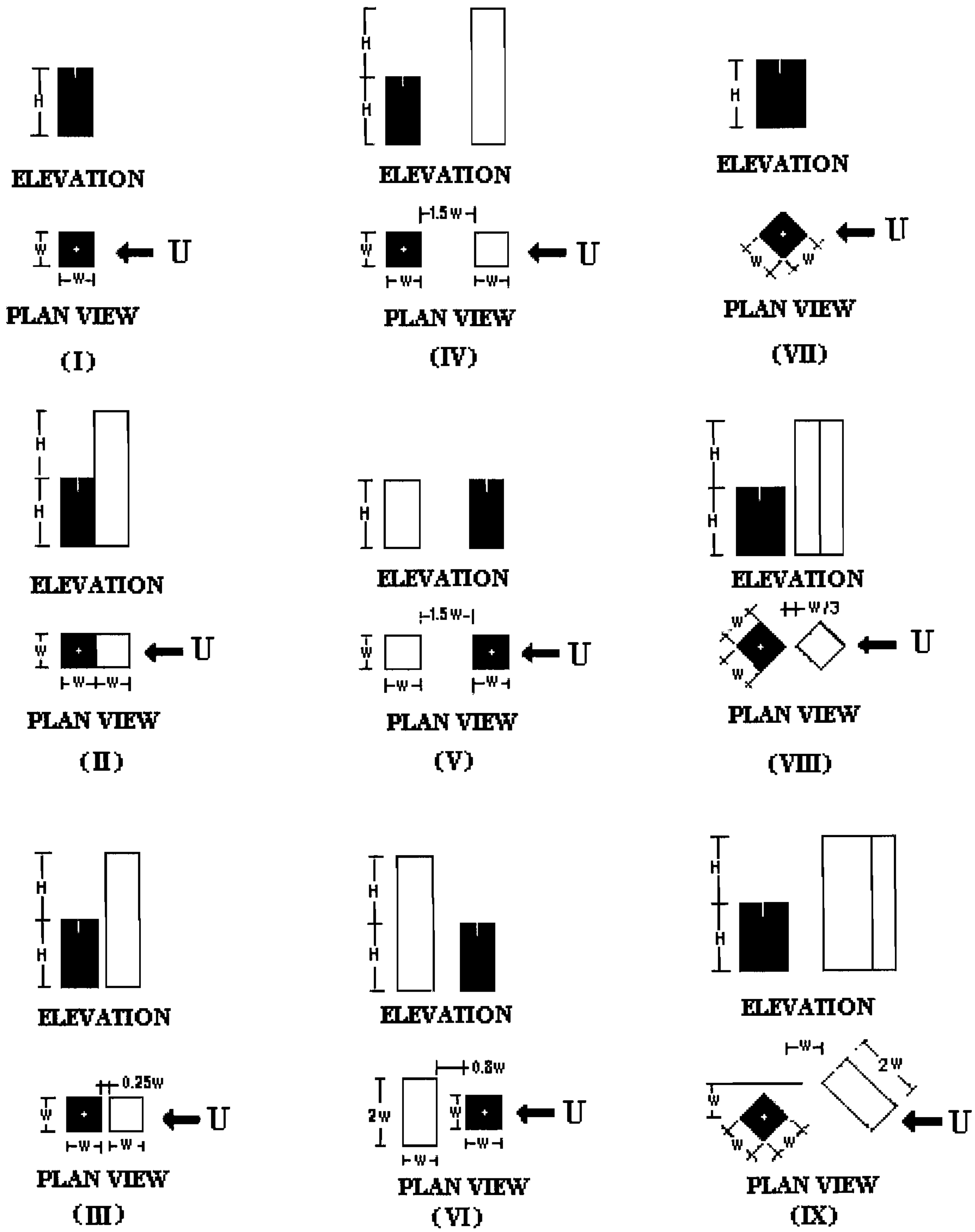
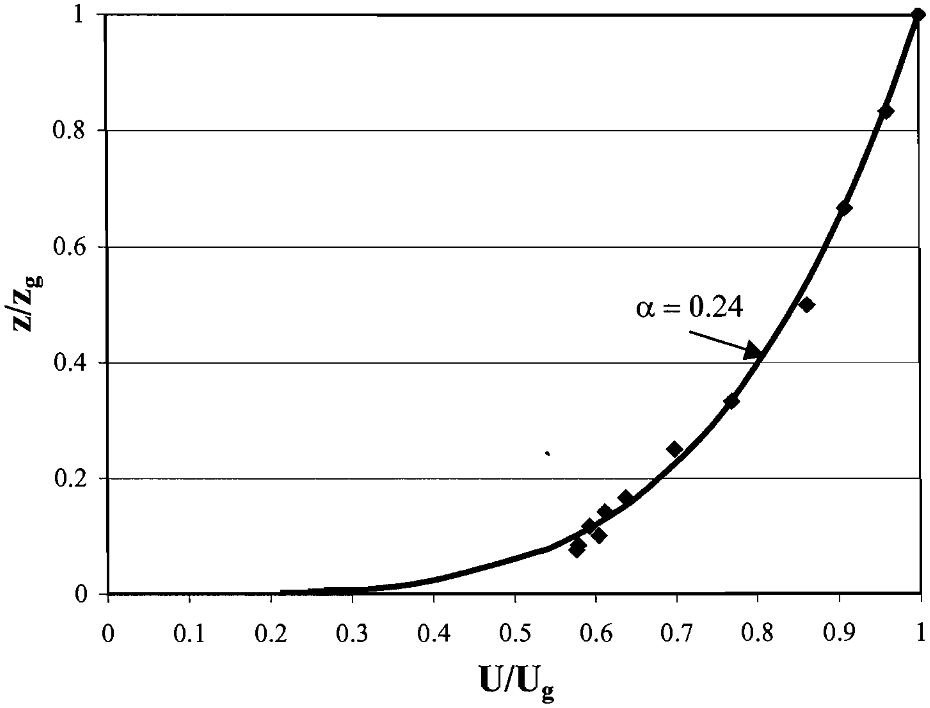
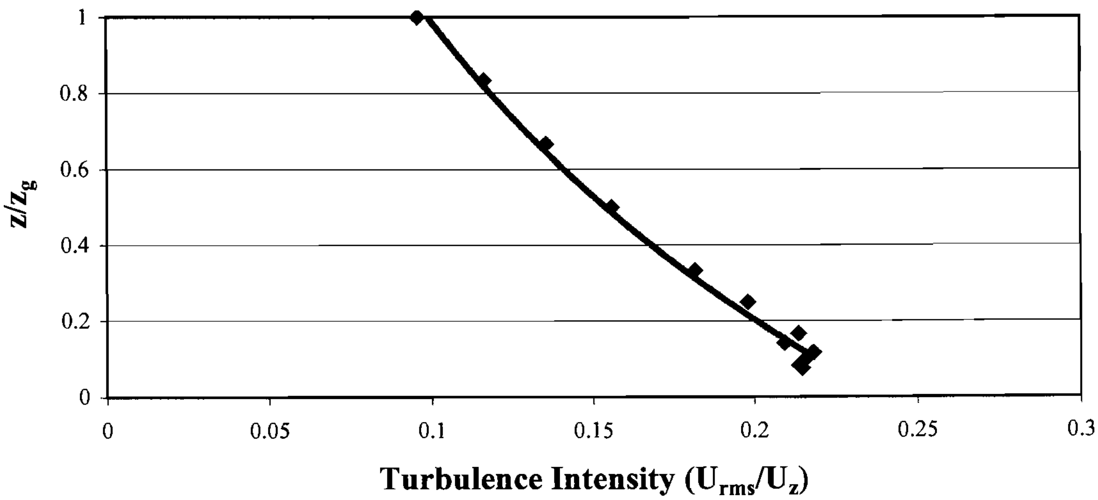


Figure 4 Configurations with Model A (square emitting building)



a) mean wind velocity



b) turbulence intensity

Figure 5 Vertical profiles of mean wind velocity and turbulence intensity

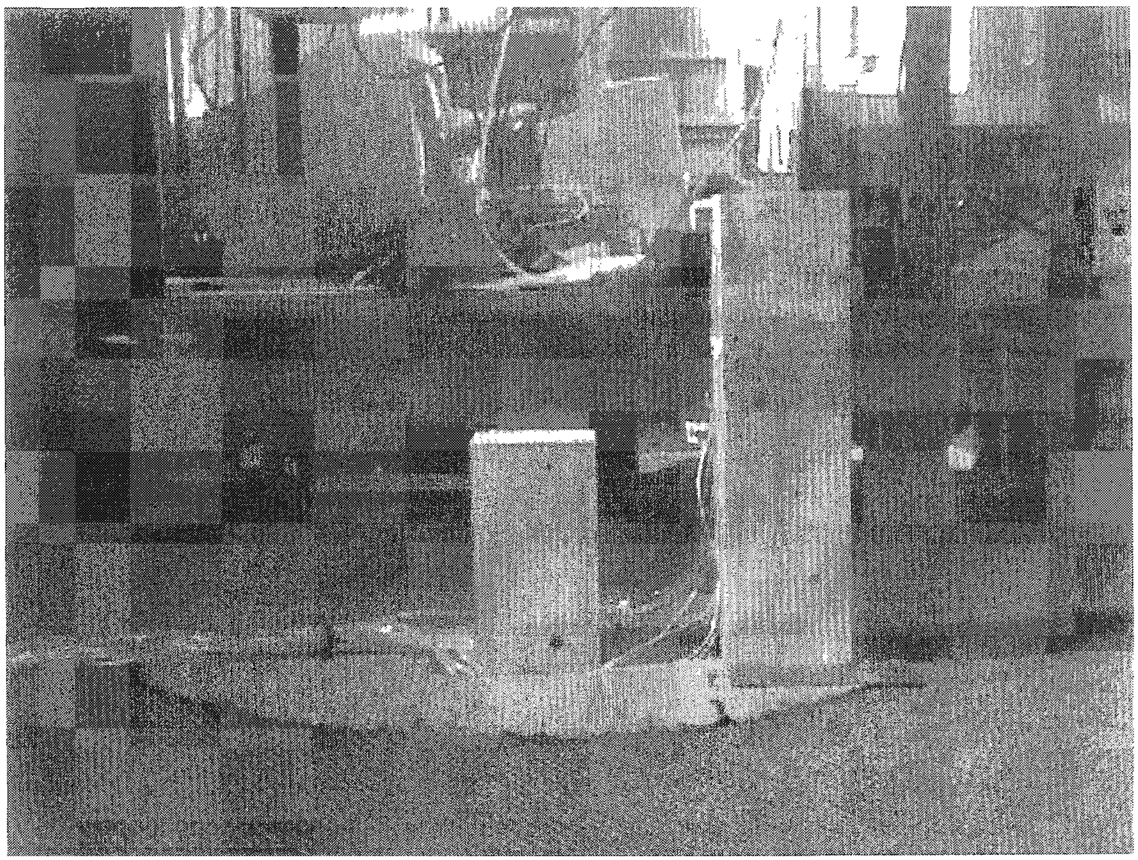


Figure 6 Photograph of wind tunnel model

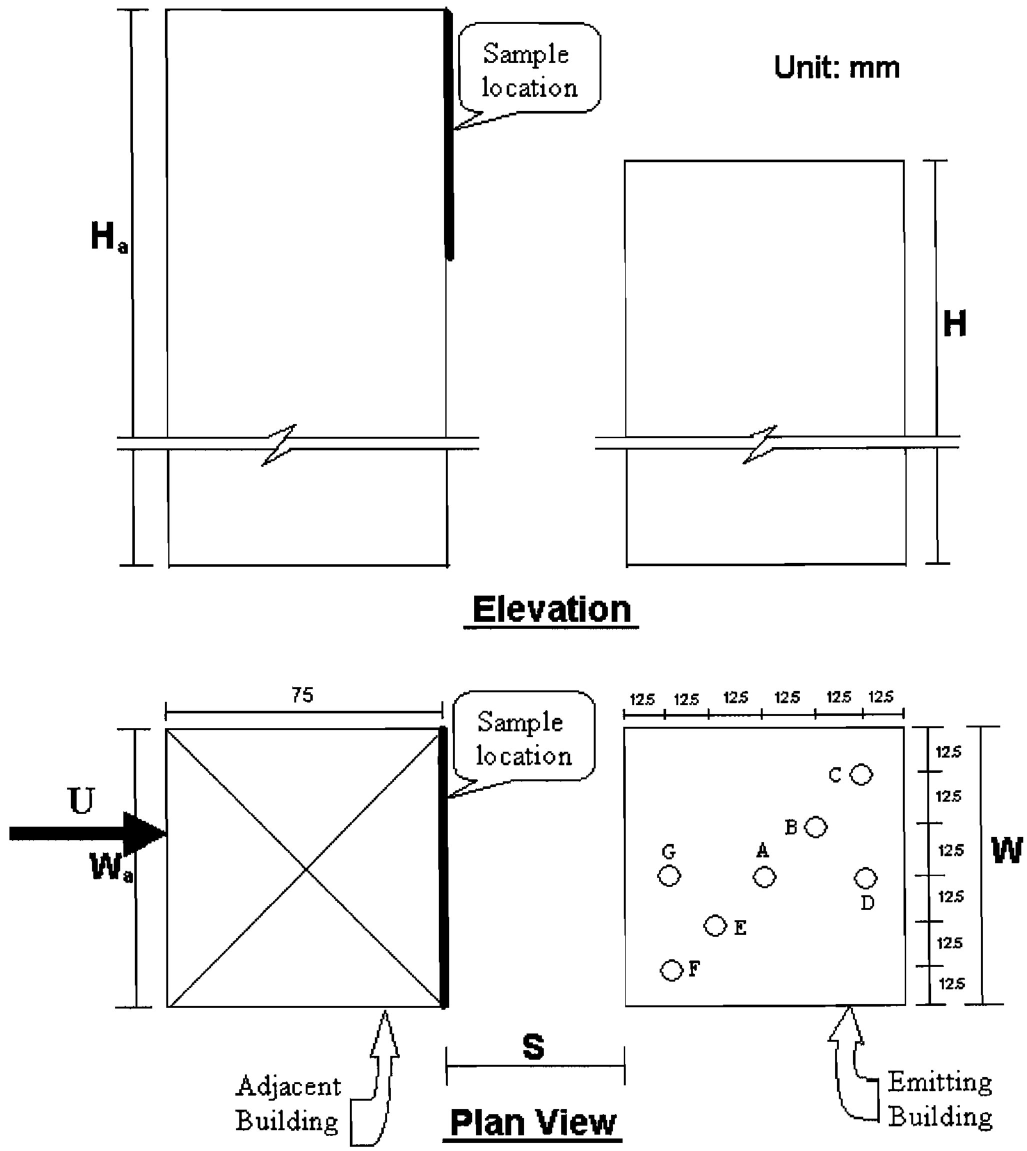


Figure 7 Locations of the outlets (Model A, $W_a = W$, $\theta = 0°$)

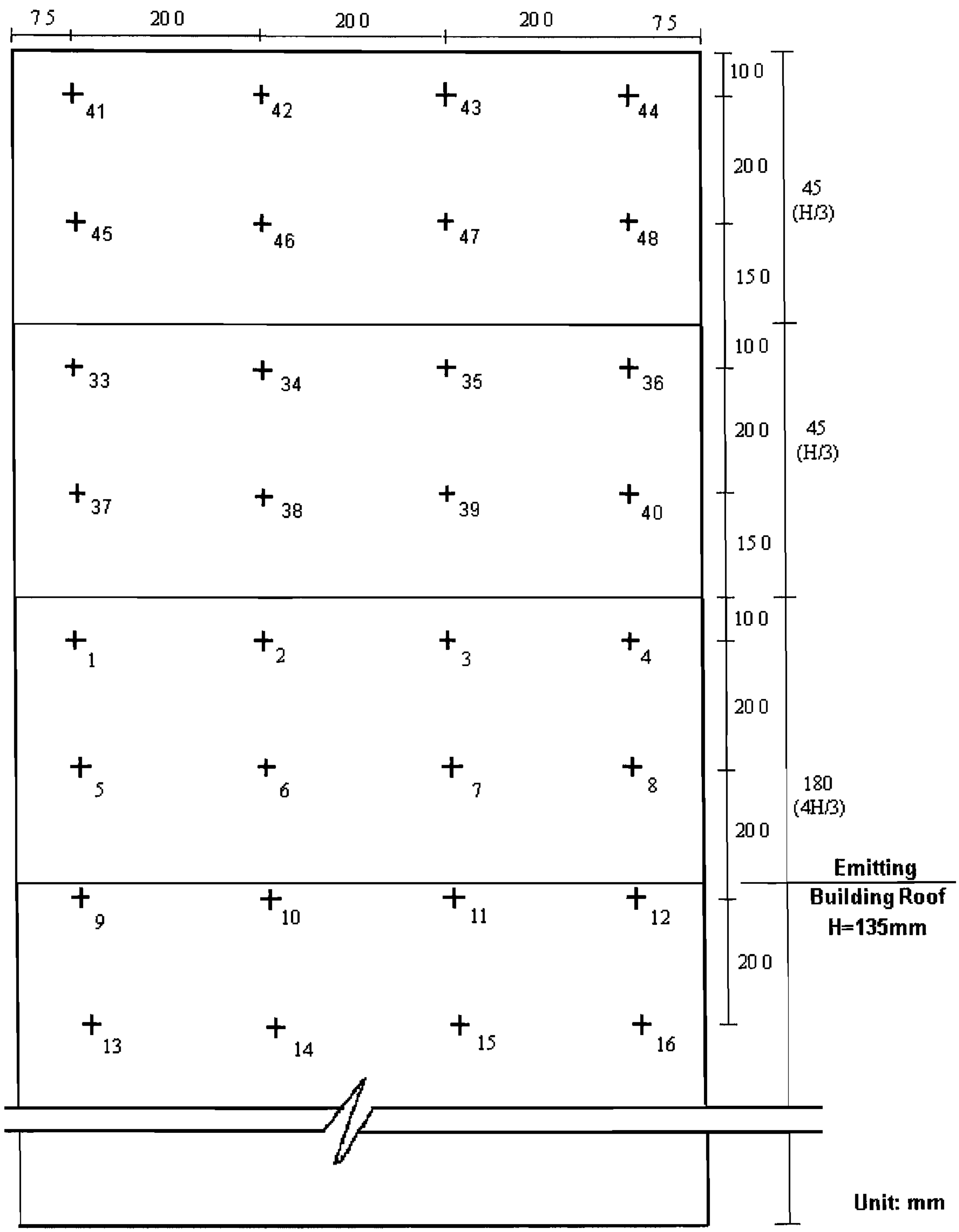


Figure 8 Locations of receptors on wind tunnel model (Model A, $W_a = W$)

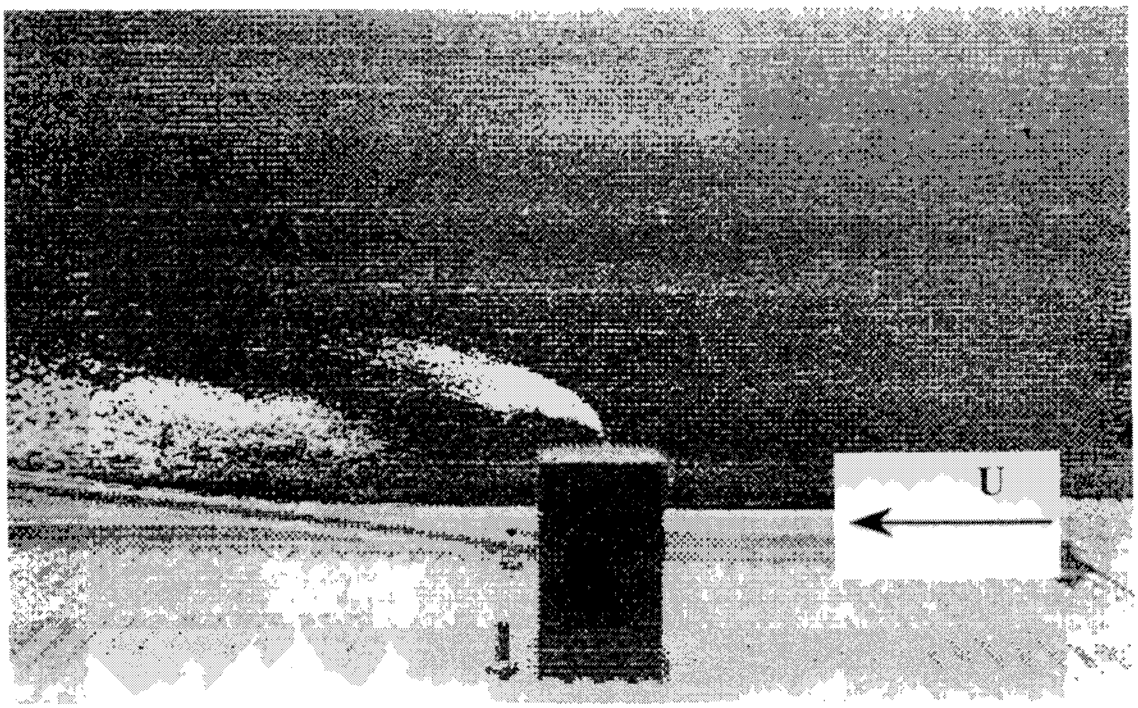


Figure 9 Visualization of plume from isolated building ($\theta = 0°$, Configuration I)

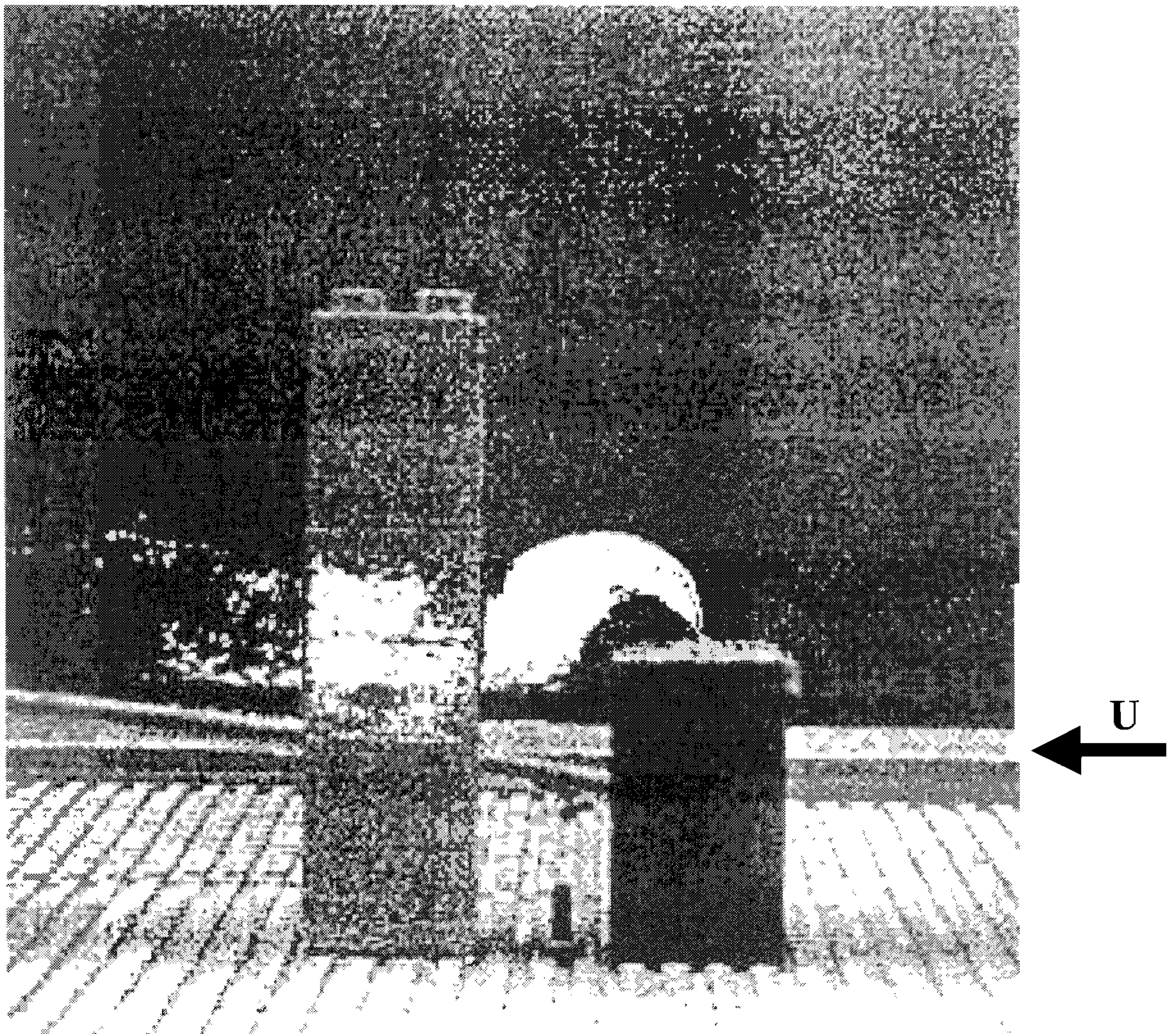


Figure 10 Visualization of plume with tall building downwind of emitting building (θ = 0°, Configuration VI)

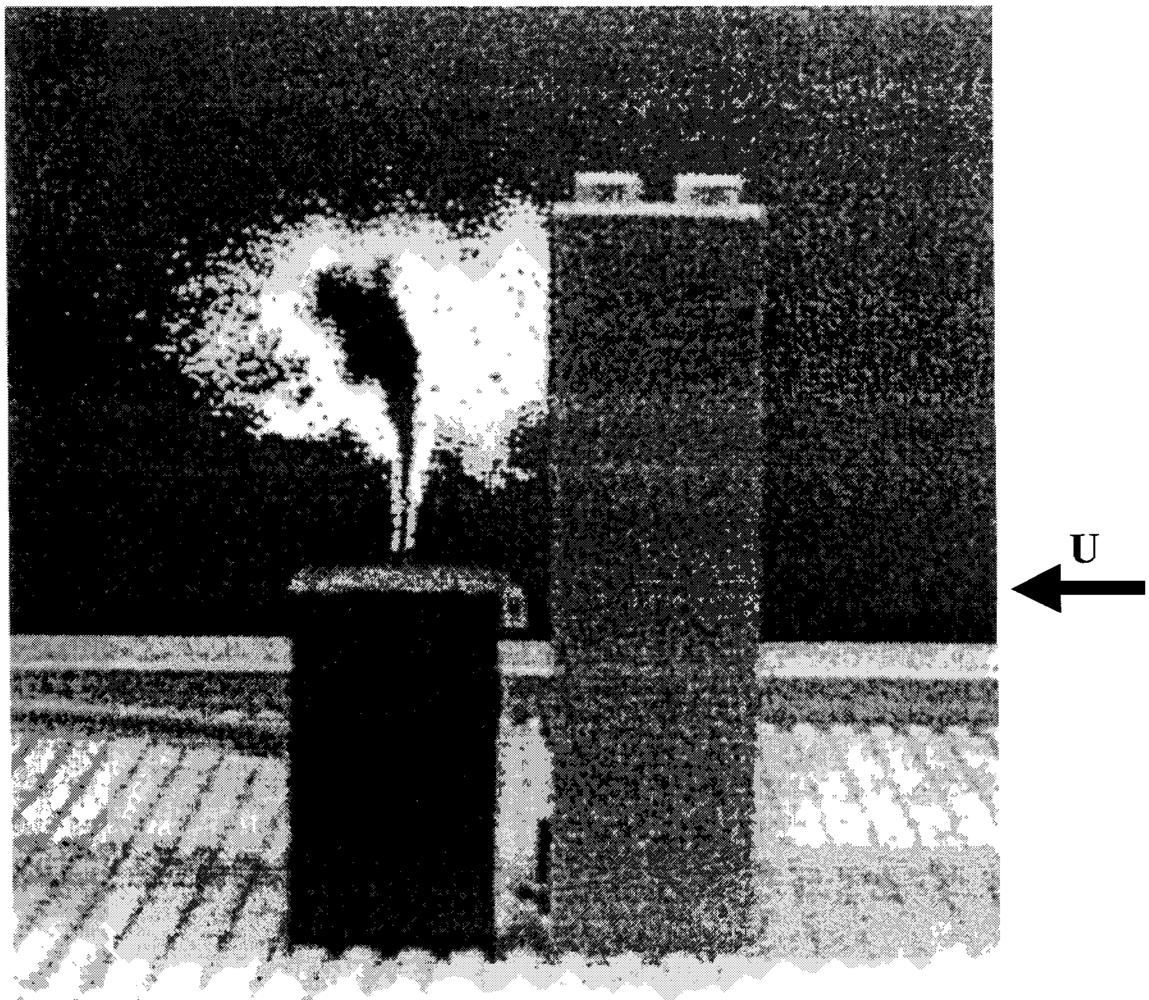


Figure 11 Visualization of plume with tall building upwind of emitting building (θ = 0°, Configuration III)

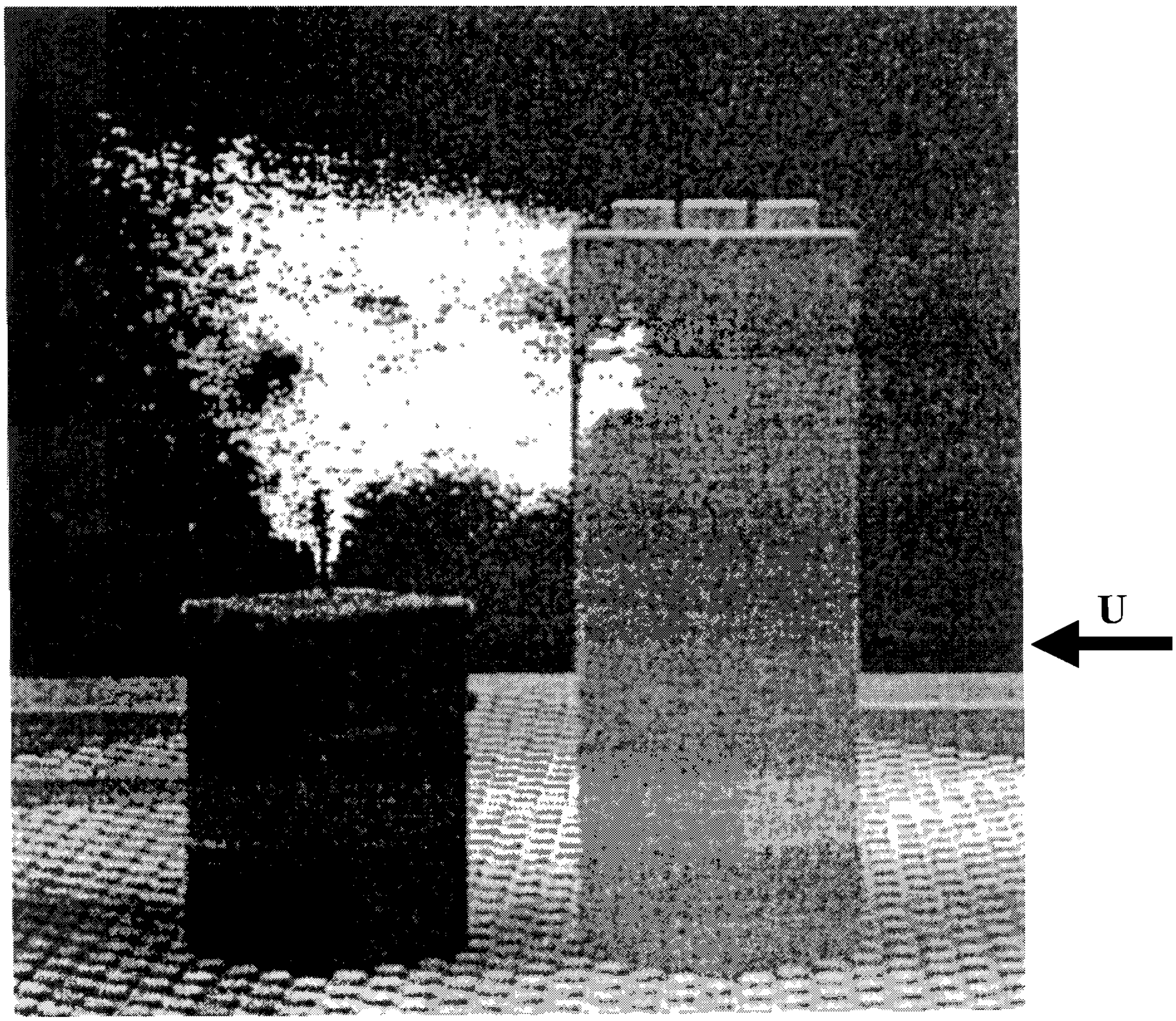


Figure 12 Visualization of plume with tall building upwind of emitting building (θ = 45°, Configuration VIII)

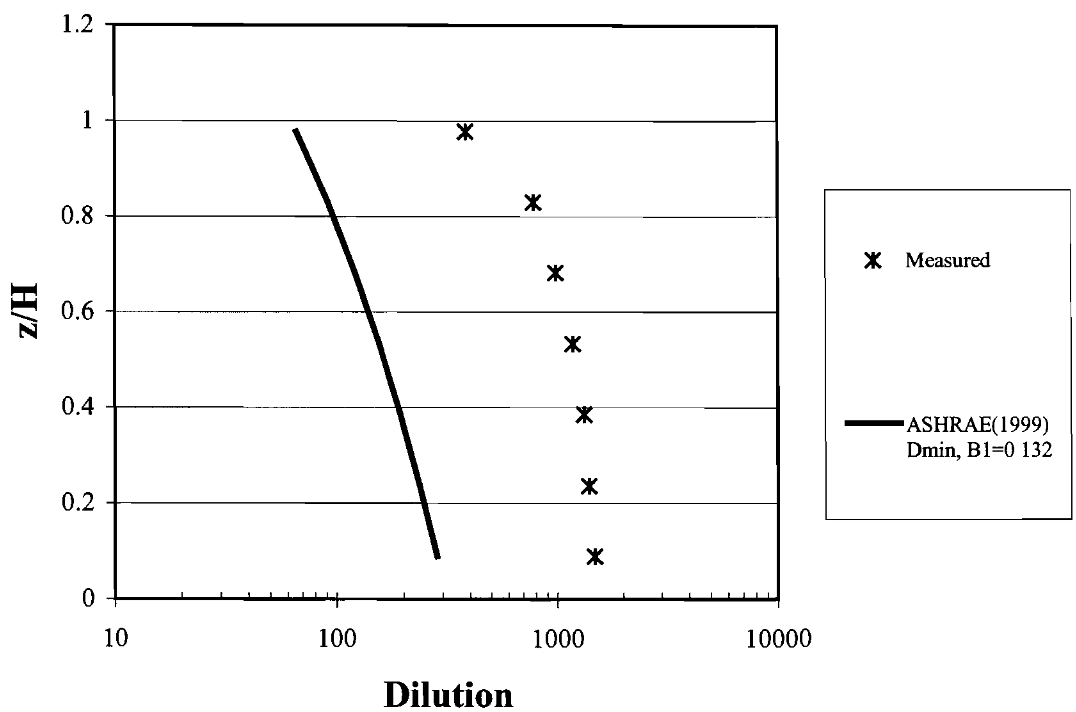


Figure 13 Vertical dilution profile on leeward wall of the isolated building (center stack, $h_s = 0$, $M = 2$, $\theta = 0°$)

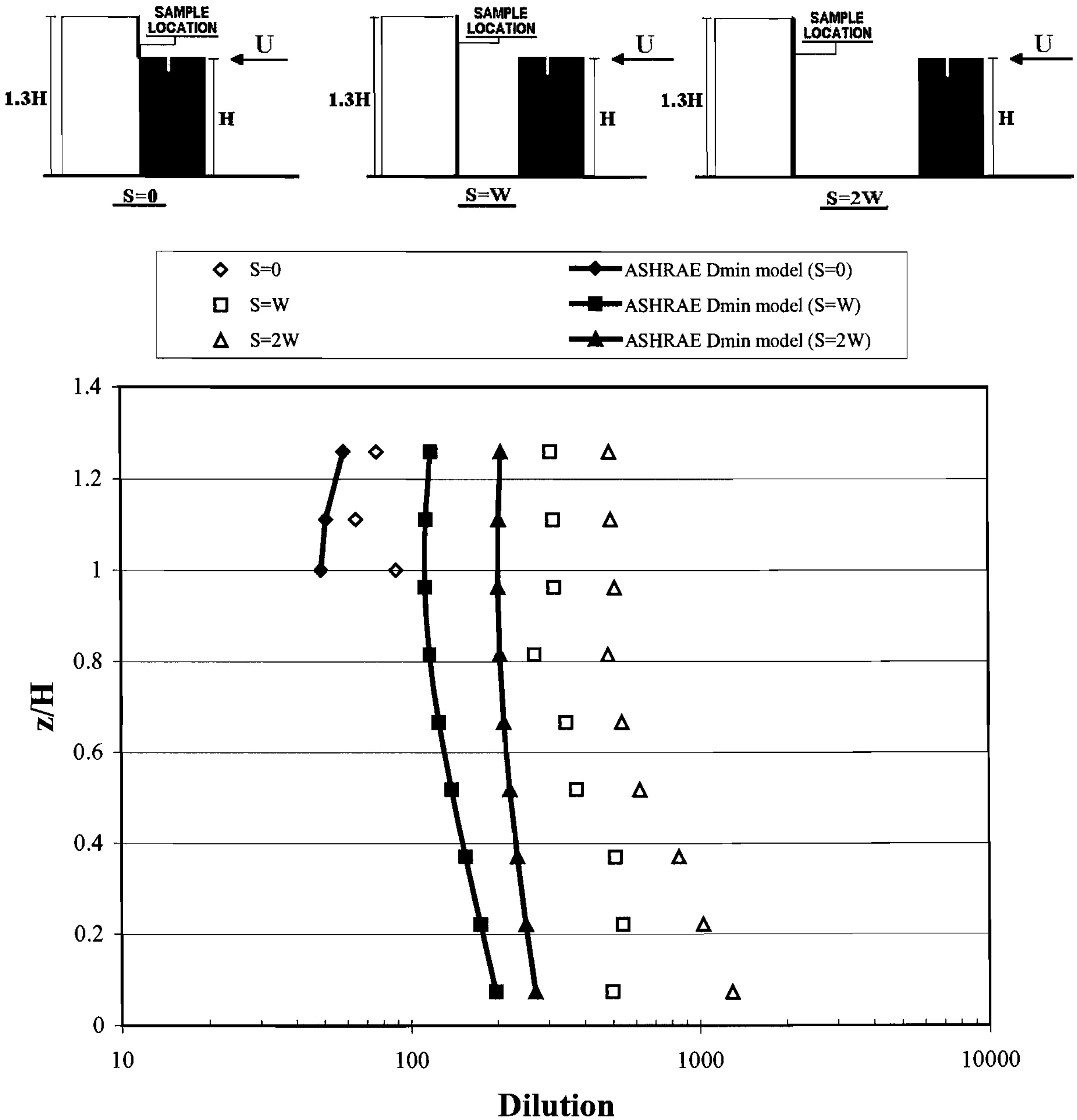


Figure 14 Vertical dilution profiles on windward wall of short single-width adjacent building (H_a = 1.3H, ASHRAE D_{min} values obtained using B_1 = 0.059)

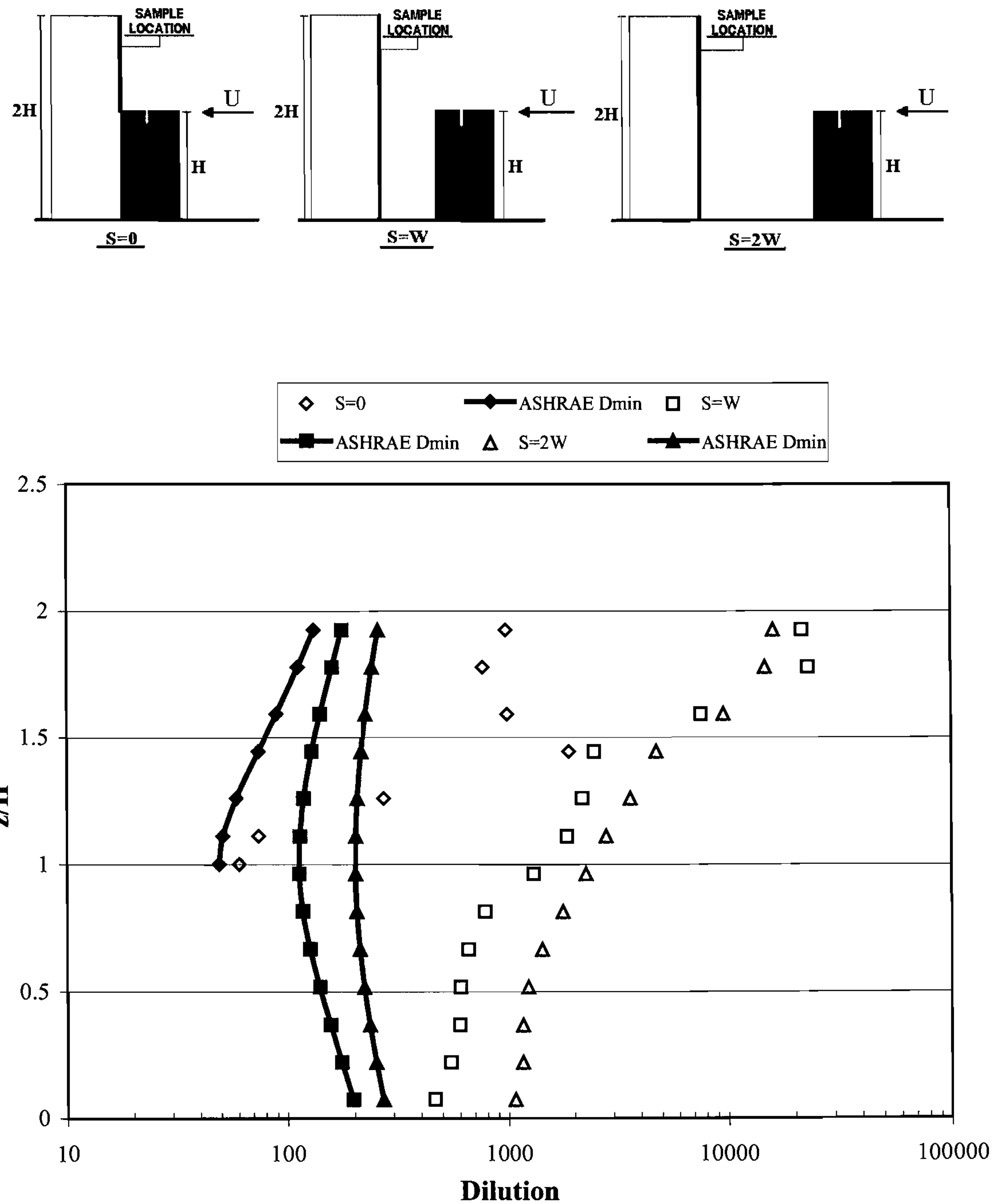


Figure 15 Vertical dilution profiles on windward wall of tall single-width adjacent building ($H_a = 2H$, ASHRAE D_{min} values obtained using $B_1 = 0.059$)

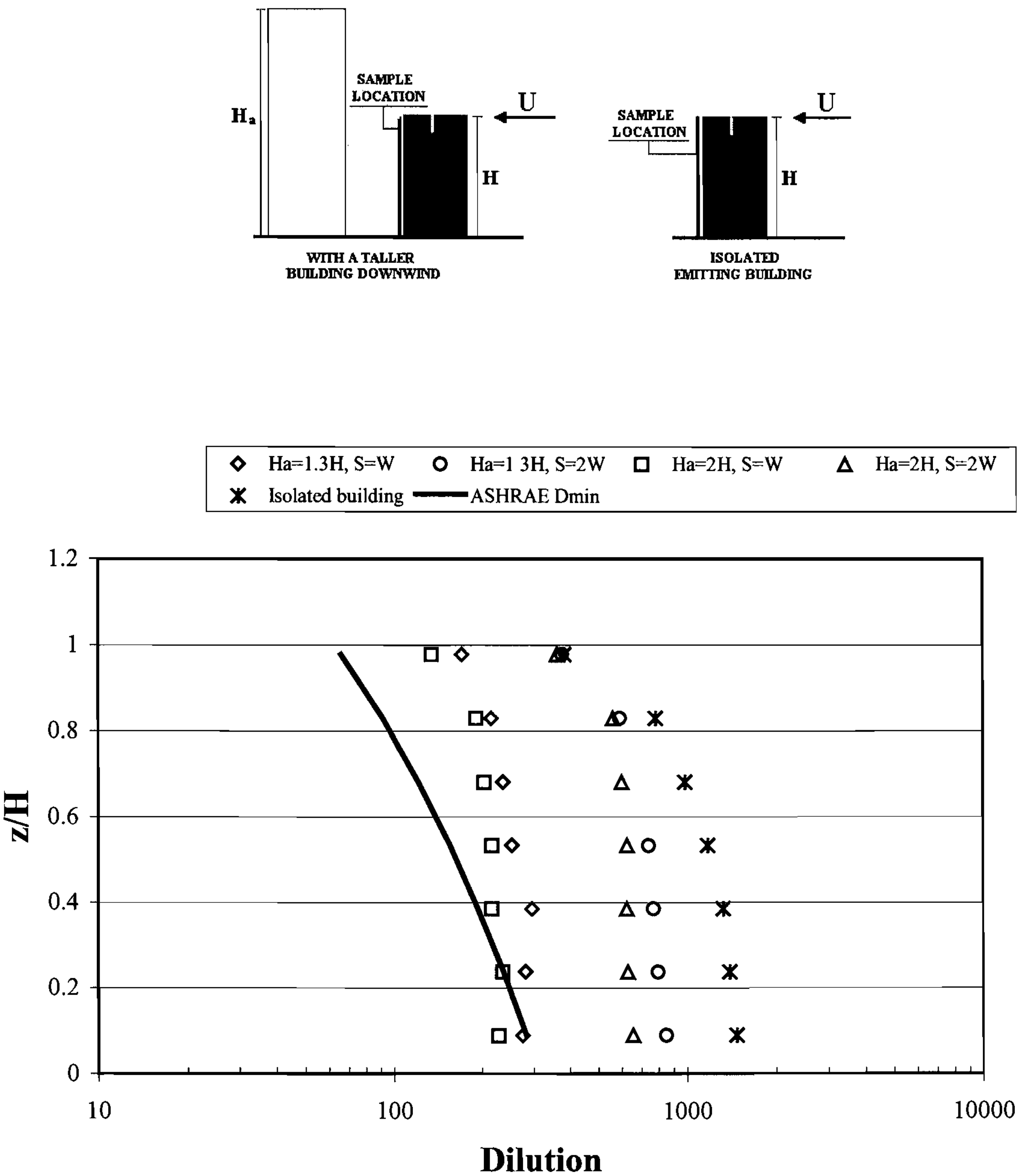
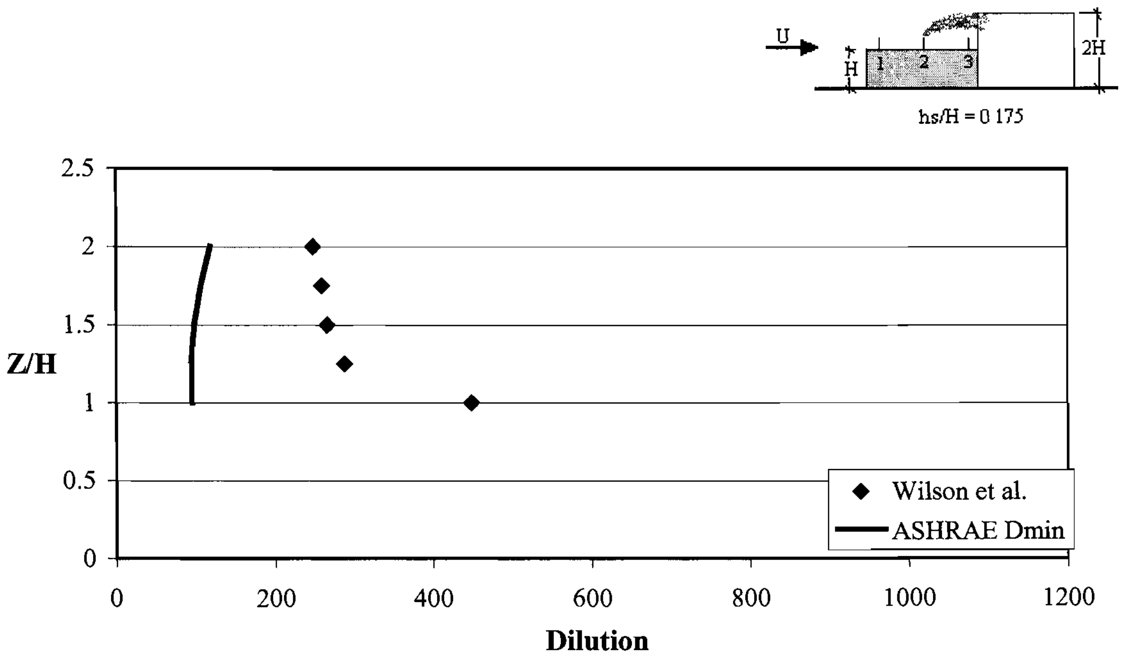
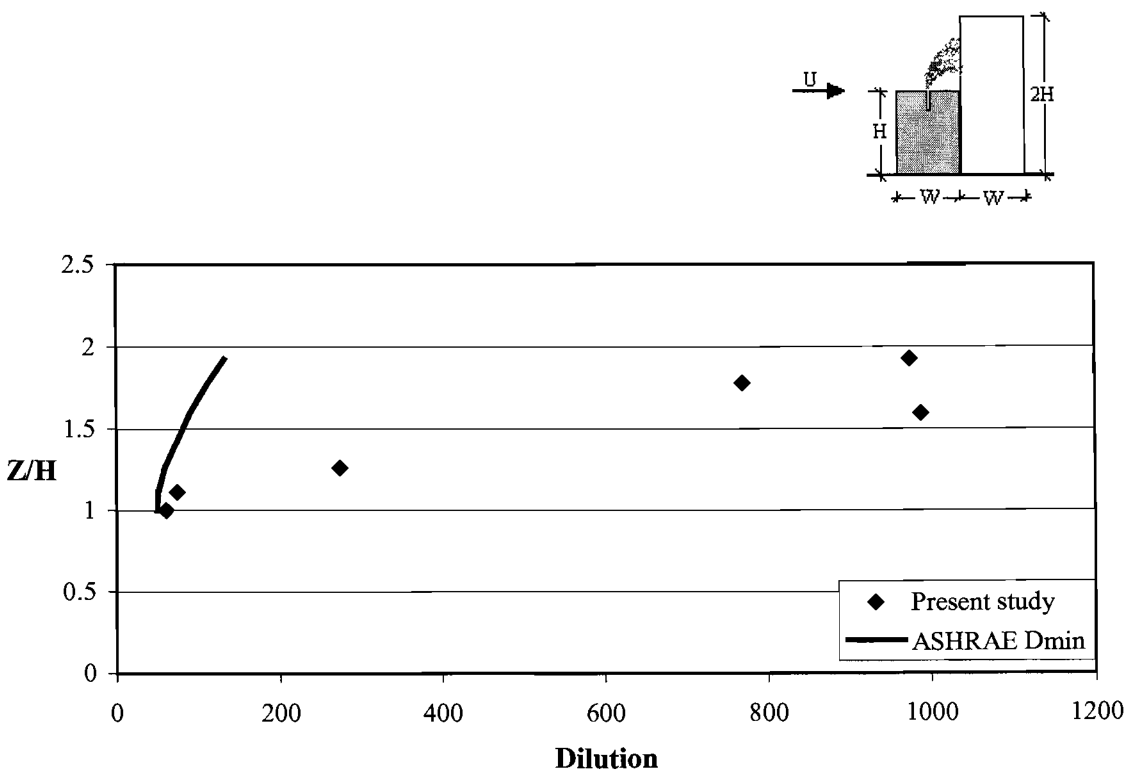


Figure 16 Vertical dilution profiles on leeward wall of upwind emitting building (H_a = 1.3H, Ha = 2H, ASHRAE D_{min} values obtained using B_1 = 0.132)



(a)



(b)

Figure 17 Dilution profile on downwind adjacent building.
Wilson model (a), present study (b). (S=0, M~2, Ha=2H)

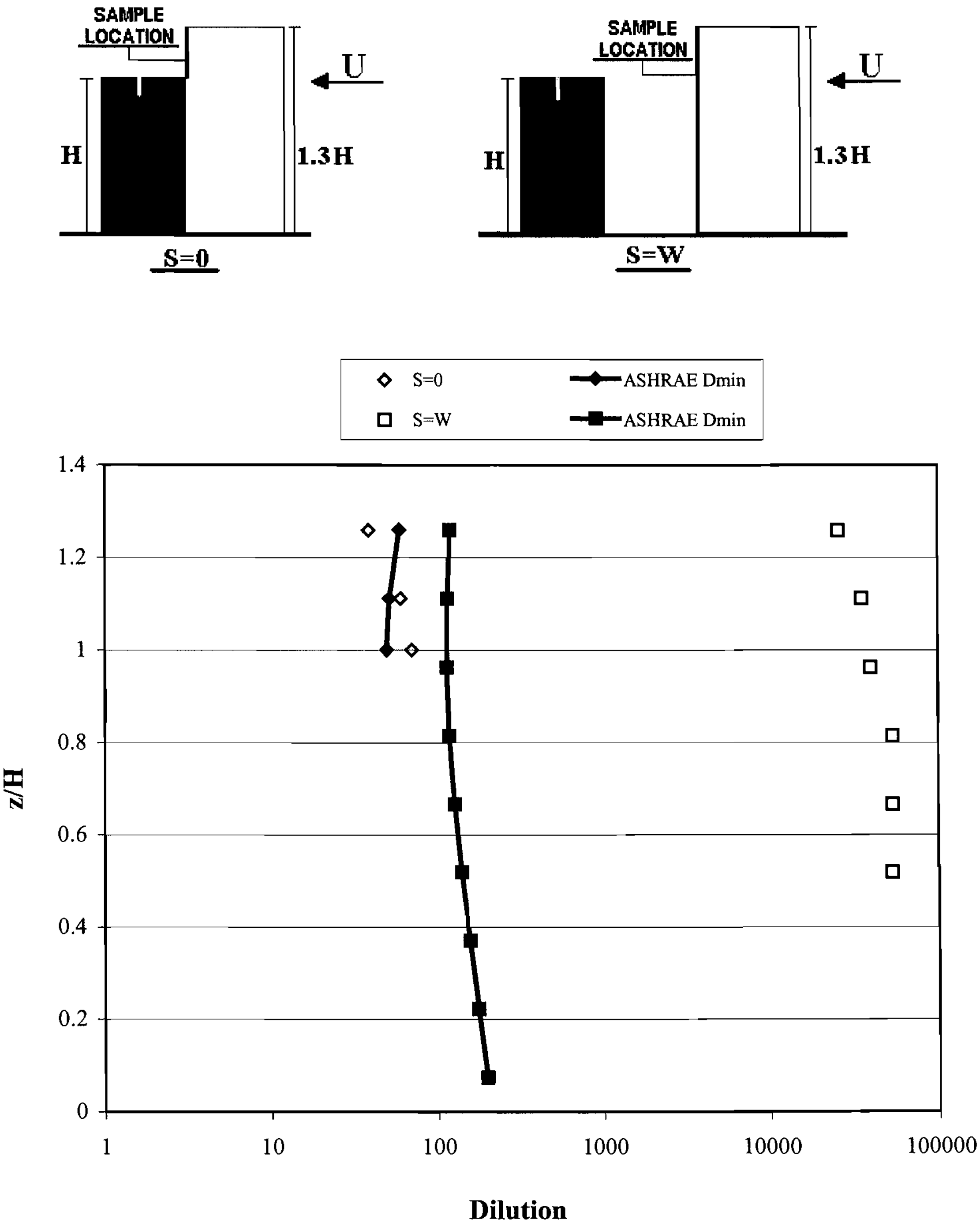


Figure 18 Dilution profiles on leeward wall of short single-width adjacent building (H_a = 1.3H) located upwind of emitting building; (ASHRAE D_{min} values obtained using B_1 = 0.059)

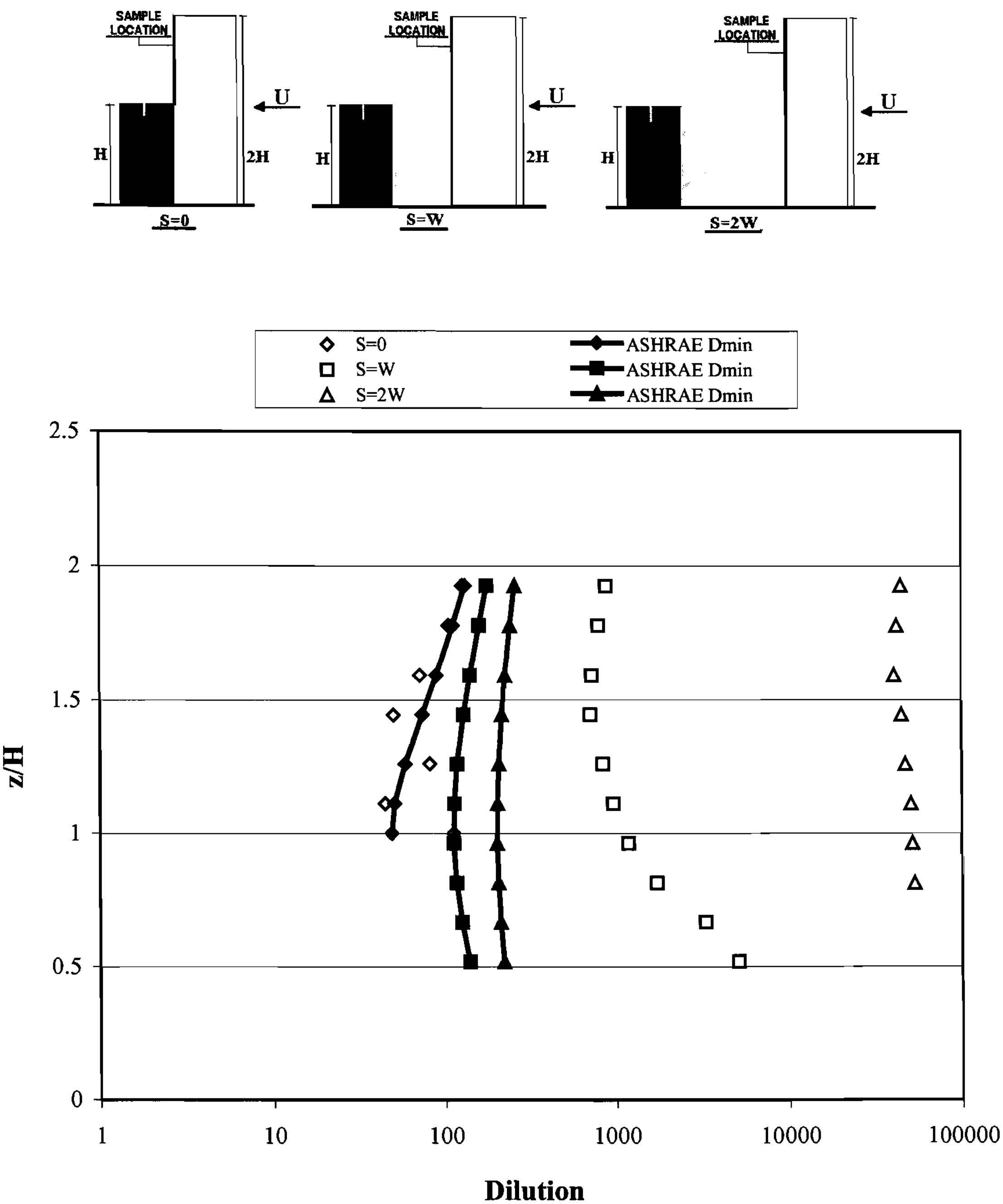


Figure 19 Dilution profiles on leeward wall of tall single-width adjacent building (H_a = 2H) located upwind of emitting building; (ASHRAE D_{min} values obtained using B_1 = 0.059)

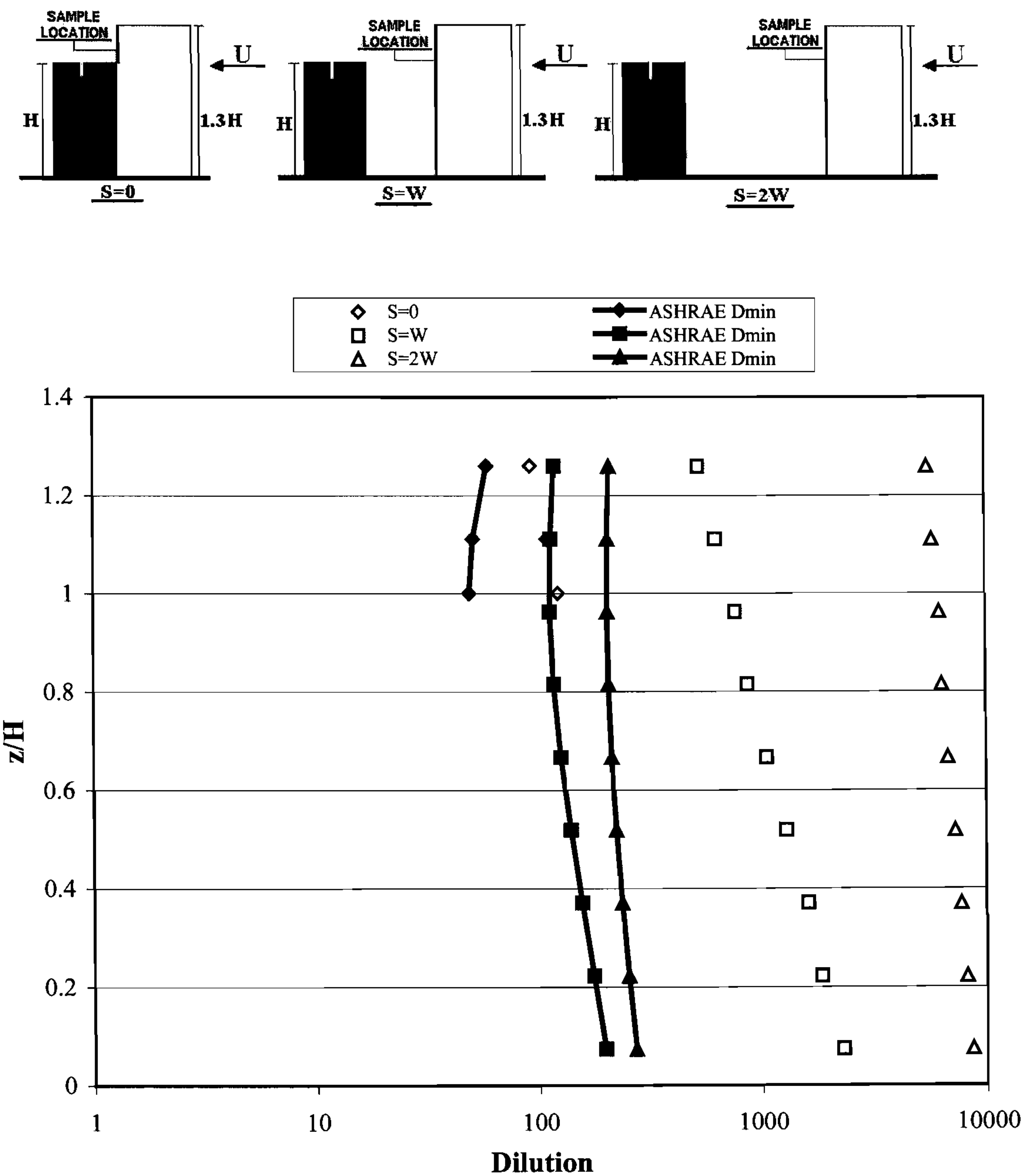


Figure 20 Dilution profiles on leeward wall of short double-width adjacent building (H_a = 1.3H) located upwind of emitting building; (ASHRAE D_{min} values obtained using B_1 = 0.059)

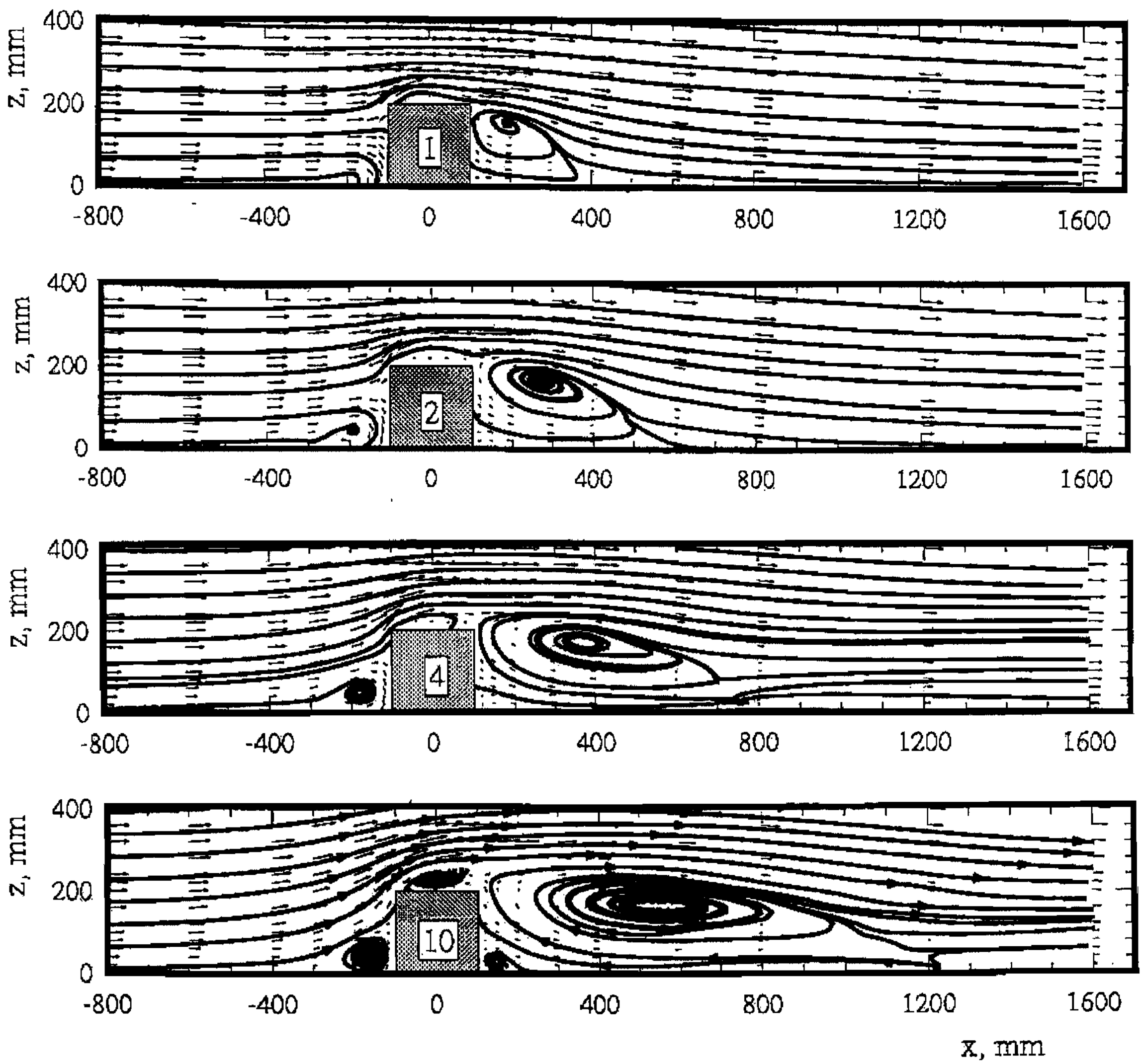


Figure 21 Streamline patterns around buildings (W = H) of various of crosswind widths. Number on building is L/H. [after Snyder and Lawson (1994)]

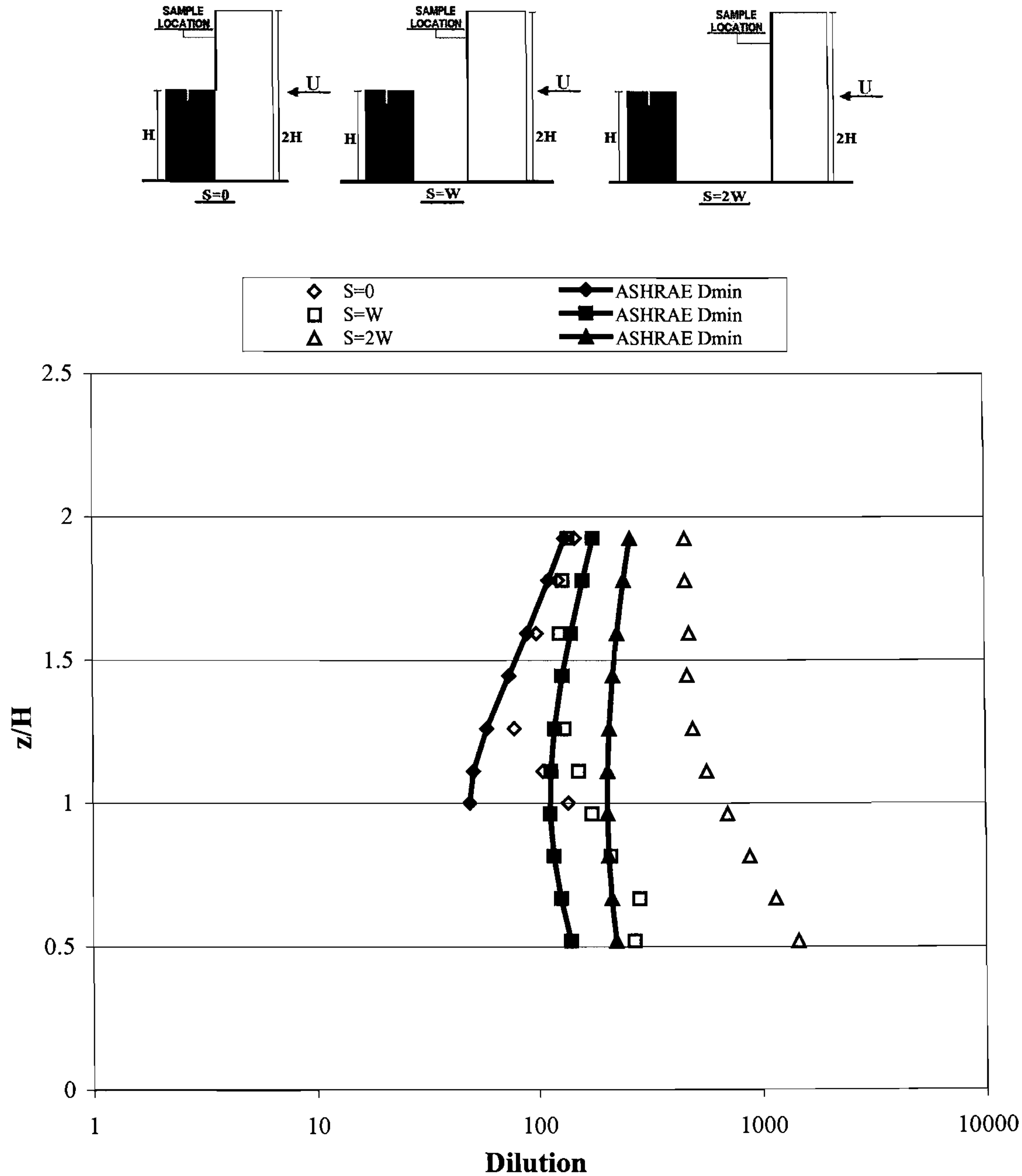
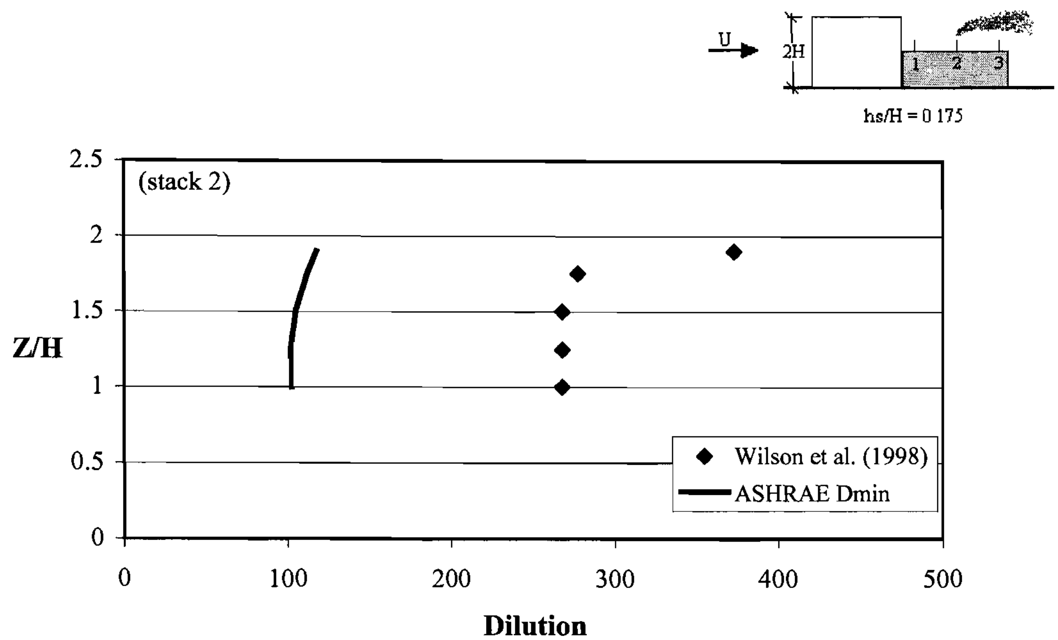
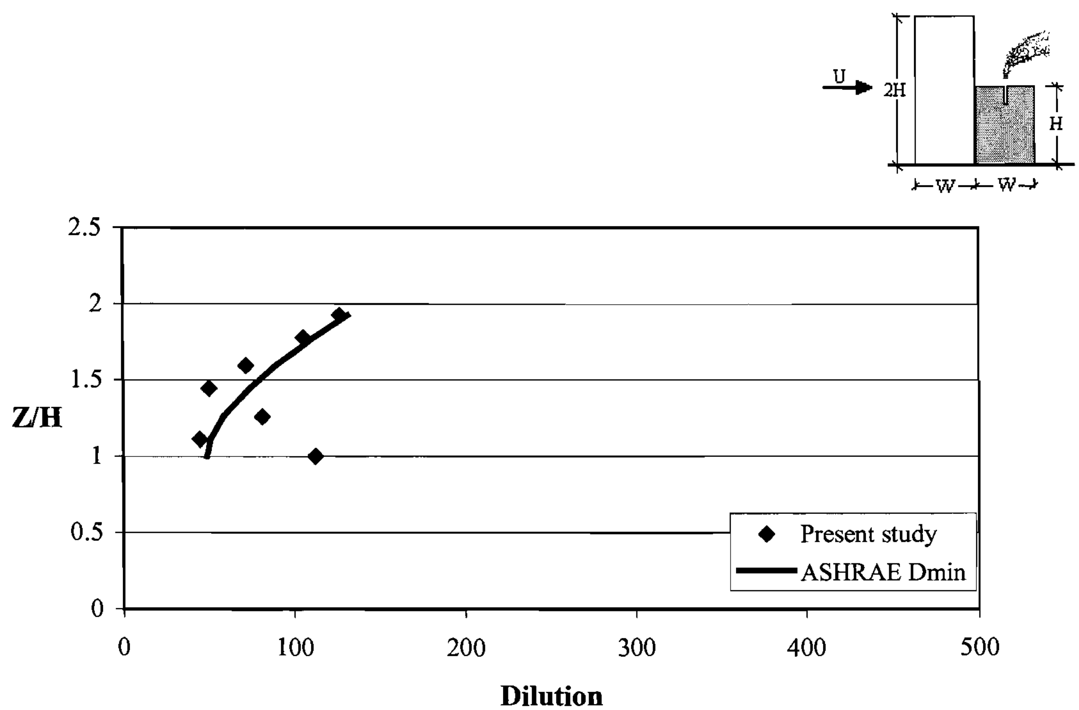


Figure 22 Dilution profiles on leeward wall of tall double-width adjacent building (H_a = 2H) located upwind of emitting building; (ASHRAE D_{min} values obtained using B_1 = 0.059)

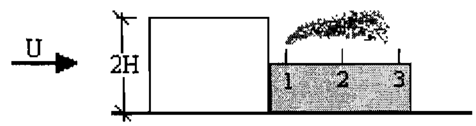


(a)



(b)

Figure 23 Dilution profiles on wall of upwind adjacent building.
Wilson model (a), present study (b) (center stack, S=0, Ha=2H, M=2)



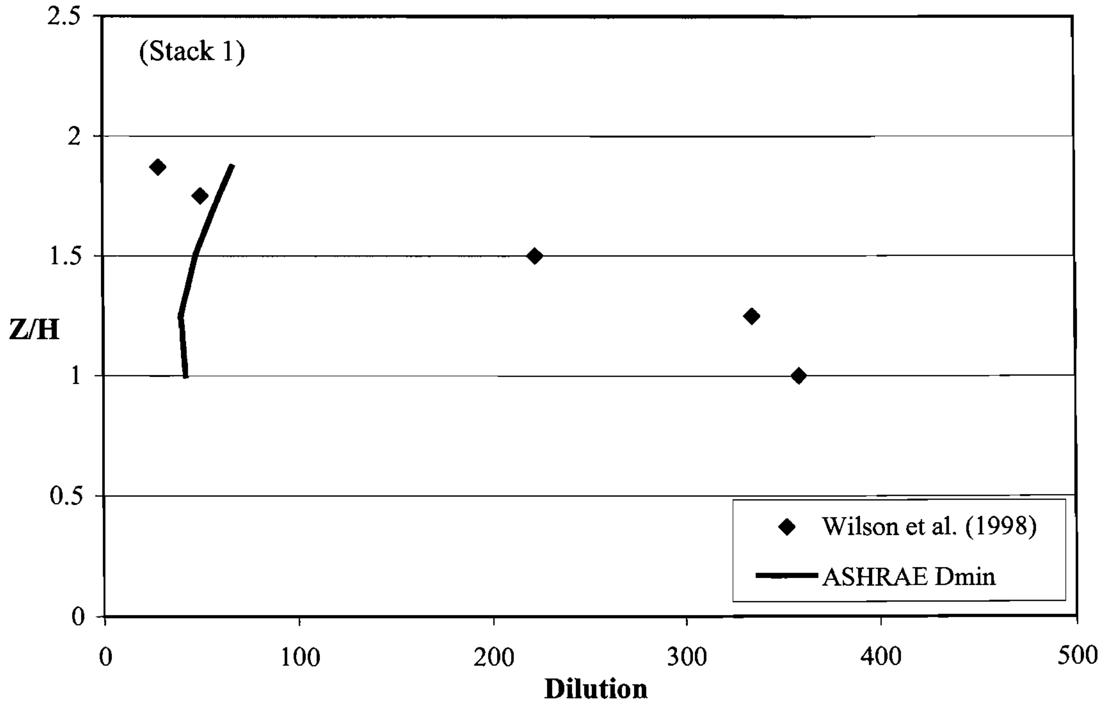
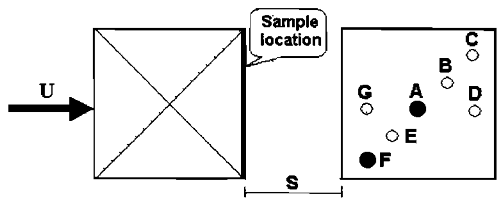


Figure 24 Dilution profile on wall of upwind adjacent building (stack 1, S=0, M=2, Ha=2H)



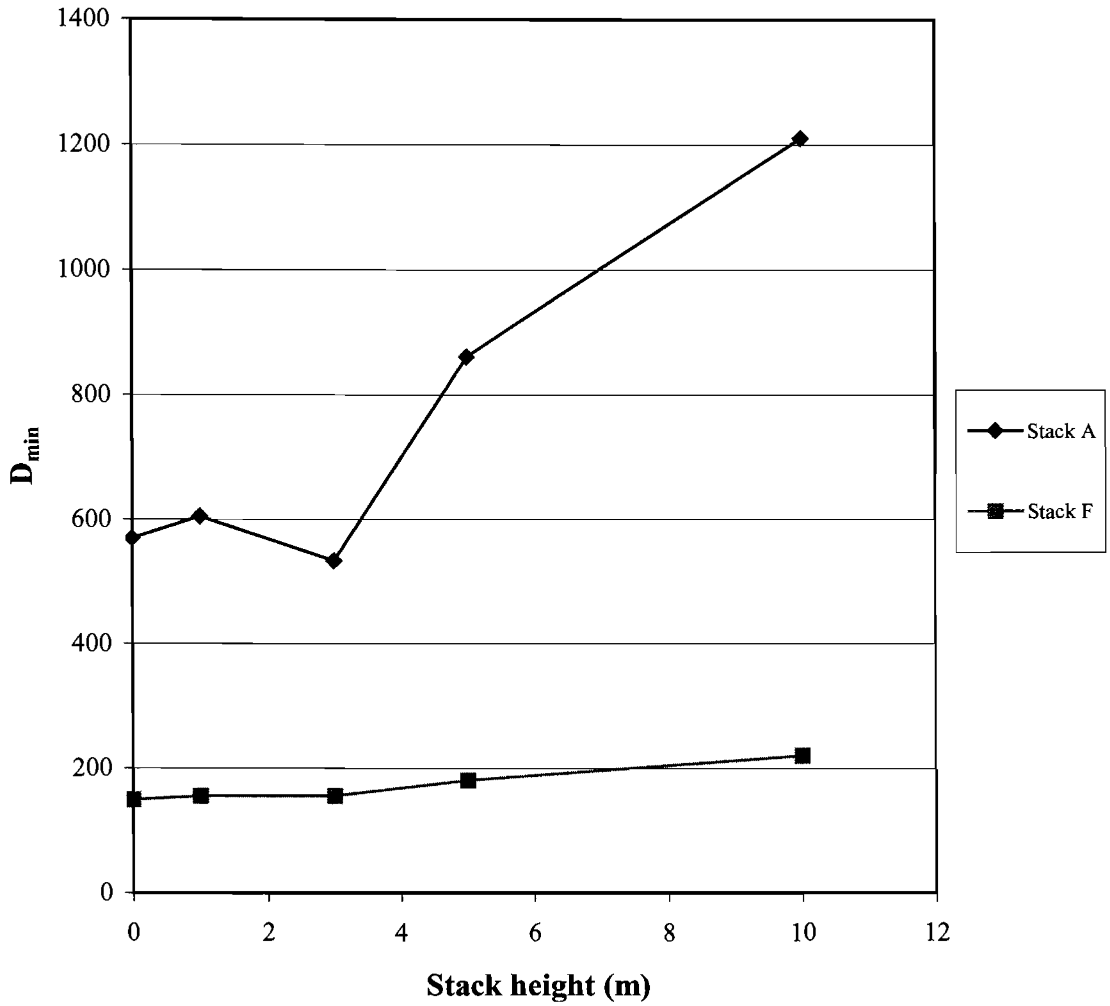
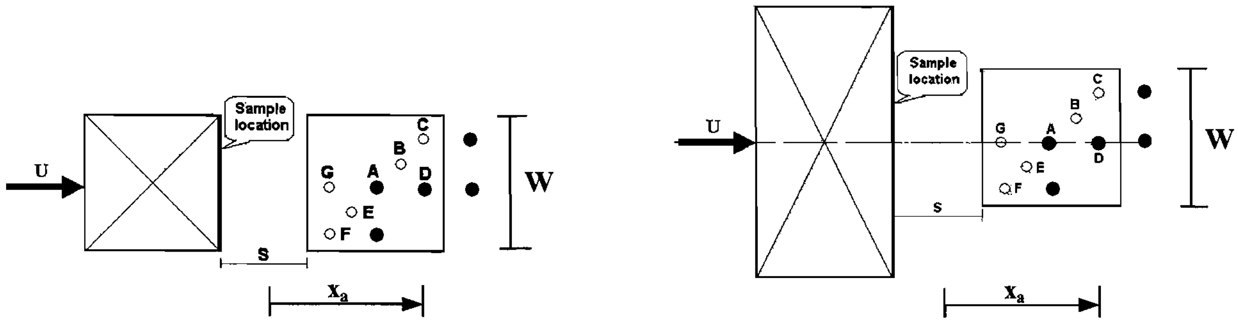
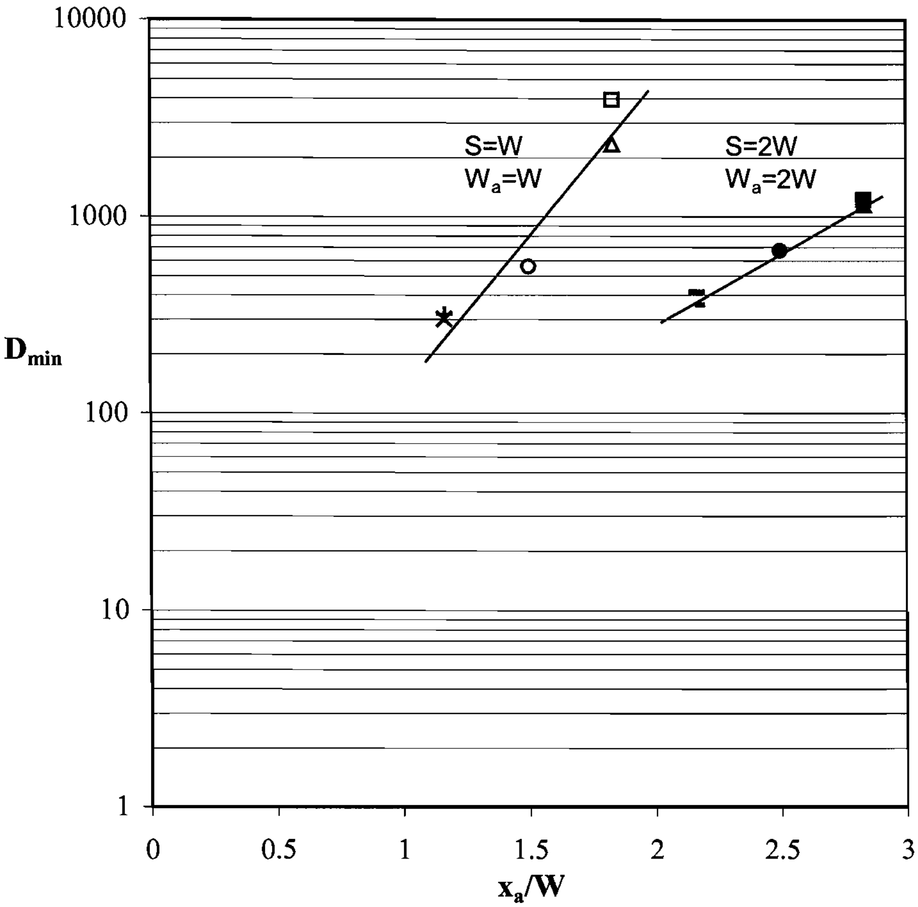


Figure 25 Minimum dilution variation with stack height for the case of $H_a = 1.7H$, $W_a = W$, $S = 0.75W$, $\theta = 0°$





Stack	Adjacent Building Width	
	Single	Double
A	○	●
C	□	■
D	△	▲
F	×	—
G	+	–

Figure 26 The effect of stack location on minimum dilution on the leeward wall of an upwind adjacent building (H_a = 2H) [x_a is the distance from a stack to the adjacent building wall]

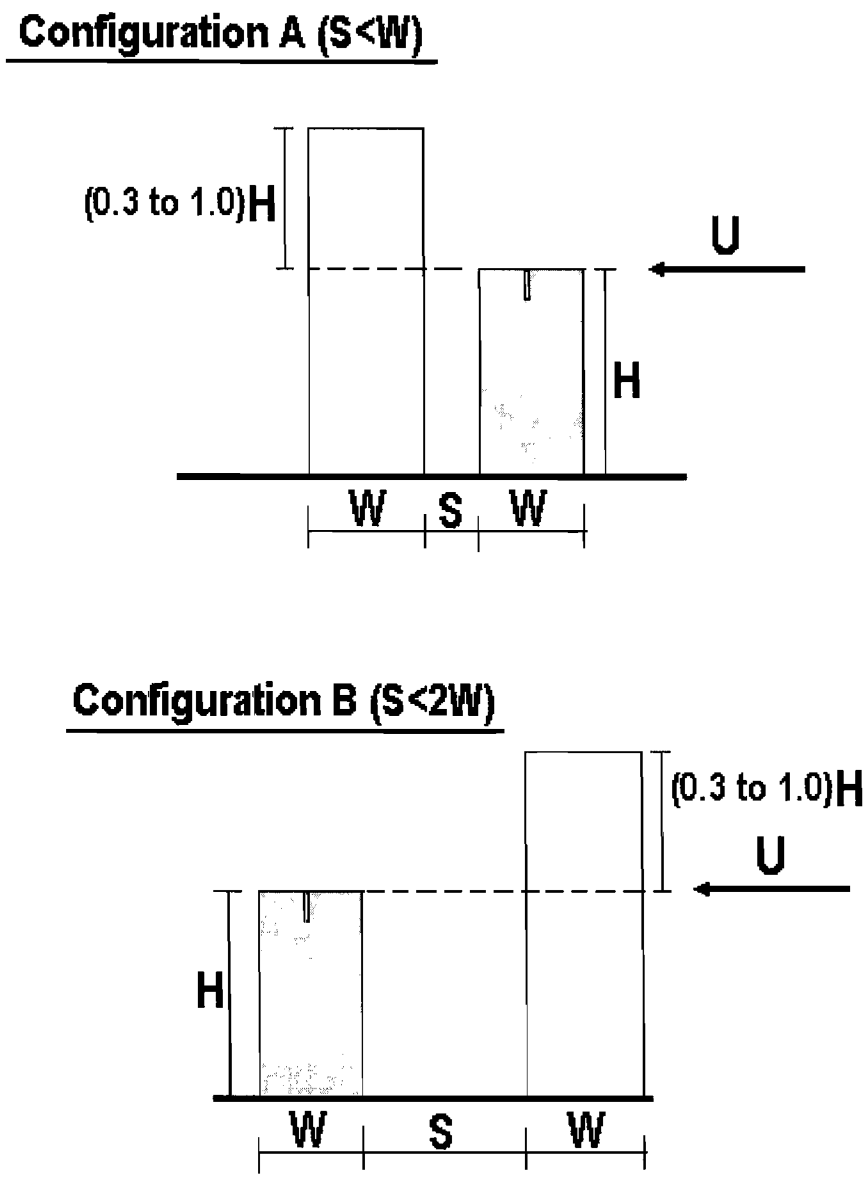


Figure 27 Potentially problematic adjacent building configurations