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MEASUREMENT OF THE EXTERIOR CONVECTIVE FILM COEFFICIENT FOR WINDOWS IN LOW-RISE BUILDINGS

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ABSTRACT

The MoWiTT field facility is used to measure the convective film coefficient over the exterior surface of a window. The MoWiTT-measured data is compared to some commonly-used experimental and theoretical models. The comparison shows that the MoWiTT data disagrees with the previously used models such as the ASHRAE/DOE-2 model. The reasons for these disagreements are discussed. An experimental model, based on the MoWiTT data, is presented to correlate the film coefficient with the difference in temperatures of the exterior glass surface and the ambient, in the natural convection region, and with the site wind speed, in the forced convection region. The wind speed is considered both in windward and leeward hemispheres. The validity of the MoWiTT model for low-rise buildings is then discussed.

INTRODUCTION

The methods used to estimate the exterior convective film coefficient have long been known to be technically unsatisfactory. For many years, ASHRAE used a "standard" value of 34 $W/m^2 \cdot K$ (6 $BTU/hr \cdot ft^2 \cdot F$) for the combined film coefficient assuming a 6.7 m/s (15 miles/hour) wind, which, after radiative heat transfer is removed, corresponds to a convective film coefficient of approximately 31 $W/m^2 \cdot K$ (5.4 $BTU/hr \cdot ft^2 \cdot F$). This value was based on early wind-tunnel measurements (Rowley 1932) using a tangential wind. Subsequent ASHRAE practice quickly interpreted Rowley's free-stream wind speed as *the ambient wind speed obtained from weather data,* an interpretation that has since ossified into laboratory practice and building simulation calculations. Rowley's work was, until very recently, the basis for calculation of the exterior film coefficient in the building simulation program DOE-2, and we call it the "ASHRAE/DOE-2" model in the following discussion. An ASHRAE committee produced a revised set of formulas for convective film coefficients (Lokmanhekim et al. 1975) based in part on measurements from the 6th floor of a medium-rise building (Kimura and Ito 1972), which we term the "Kimura 6th floor" model. This model predicts a value of 25 $W/m^2 \cdot K$ (4.4 $BTU/hr \cdot ft^2 \cdot F$) for the convective film coefficient at a 6.7 m/s (15 miles/hour) wind speed, which is somewhat lower than the "ASHRAE standard" value given by the ASHRAE/DOE-2 model. The Kimura 6th floor model is used in the program WINDOW to calculate window U-value for 6.7 m/s (15 miles/hour) wind ("standard condition") or for other user-specified conditions. Kimura (1977) also presented a set of equations summarizing Ito and Kimura (1972) measurements made at the 4th floor of the same medium-rise building. We denote these equations the "Kimura 4th floor" model.

A careful survey of the literature on exterior film coefficients (Furler 1988) found as many as 14 sets of equations for predicting the external convective film coefficient, with wide variations

between the predictions. The data from which the equations were derived included both laboratory and field measurements in a variety of conditions. The most credible of the measurements on buildings, however, applied to either medium-rise (4-6 floor) or high-rise buildings, and clearly indicated that film coefficients increase with height.

The exterior film coefficient is an important issue for window performance. Until the relatively recent emergence of low-E and other thermal resistance windows into prominence in the window market, windows had low intrinsic thermal resistance, making the exterior film coefficient a strong determinant of the window nighttime U-value. Even for the newer generations of window products, the exterior film coefficient does not become entirely unimportant until one reaches the realm of "superwindows", i.e., thermal resistance in the range of 1.4-1.8 $m^2 \cdot K/W$ (8-10 $hr \cdot ft^2 \cdot F/BTU$).

The importance of this issue quickly became apparent in our studies of window thermal performance under realistic conditions. In this work we present a series of field measurements of the exterior film coefficient seen by windows under a variety of nighttime conditions of wind and temperature.

MEASUREMENT OF EXTERIOR FILM COEFFICIENT

Measurements were made at the Lawrence Berkeley Laboratory Mobile Window Thermal Test (MoWiTT) facility at its field site on the campus of the University of Nevada in Reno, NV. The MoWiTT, which has been described elsewhere (Klems et al., 1982; Klems 1984), consists of two side-by side, guarded, room-sized calorimeters mounted in a common envelope. Each calorimeter continuously measures the net heat flow through a selected test window of approximately 1 m^2 (3 x 4 ft) area. When a frameless sheet of glass is used as a test window and the mean temperature of the glass monitored, then the net heat flow at nighttime can be used to derive an effective exterior (as well as interior) film coefficient. The data is averaged over ten-minute intervals, and the thermal response of the calorimeters is sufficiently rapid to make these averages meaningful.

A number of factors complicate the measurement of exterior film coefficients. In laboratory measurements, for both forced and turbulent natural convection, the mean film coefficient depends on the size of the area over which it is measured, on the surface roughness and on the geometry of the surroundings. For building energy analysis, it is almost never useful to model the specific, geometry-dependent convective film coefficient applicable to a particular situation because of the labor necessary to apply such a model (for example, one would need to know the complete wind flow field as a function of time and to model separately each window in a building); instead, what is desirable is a simple average film coefficient that can be applied to a range of situations independent of geometry—or, perhaps, to a specifiable class of geometries. This creates ambiguities about how to apply measurements taken with modest sized sensors, either in a laboratory or on a building, to a window measurement. For this reason, we believe that the measurements made in the MoWiTT—with a full-sized window mounted in a reasonable facsimile of a wall—give a realistic measurement of the average exterior film coefficient for a window in a low-rise building. We show below that a specially-designed film coefficient meter

of similar exterior geometry produced the same results. Of course, application of this data to windows of very different geometry or setting will introduce new ambiguities; however, one at least begins with realism.

Appendix A presents the equations used to determine the convective film coefficient on the exterior surface of a window. All of the quantities needed (in Equation A-6) are directly measured. The net heat flow, Q_{net}, through the window is accurately determined from the calorimeter instantaneous heat balance or by a specially designed heat flow meter described below; the incident thermal radiant flux, I_R, is measured by a vertically mounted pyrgeometer that views the same hemisphere as the windows and monitors the long wave infrared flux from the sky (and ground); the ambient air temperature, T_{out}, is measured with a thermistor mounted in an aspirated shield on the MoWiTT's weather tower; and T_{glass}, the exterior glass temperature, is measured by thermistors installed on the outside surface of the window. Previous tests of the thermistor mounting methods had indicated that at night the thermistors measure the true glass temperature within a few tenth of a degree. The on-site weather tower also measures wind speed and direction at a 10-meter height.

During some of the MoWiTT tests, a frameless single glazing window was mounted in one of the calorimeters while the glazing of interest was simultaneously measured in other chamber. The single glazing data, which include a measurement of the glass temperature, provide a direct, simultaneous measurement of both inside and outside film coefficients. However, it did not prove economical of resources to devote one of the MoWiTT calorimeters continuously to measurement of exterior film coefficient. We therefore constructed a film coefficient meter (FCM) to duplicate the essential functions of the MoWiTT measurement of the exterior film coefficient, and this device was run continuously while other window measurements were being made with the calorimeters.

The Film Coefficient Meter (FCM), described in appendix B, is mounted on the exterior surface of the MoWiTT, between the two calorimeter openings as shown in Figure 1. The three heat flow sensors installed in the FCM assembly measure Q_{net}/A and four thermistors installed on the FCM's exterior glass surface measure T_{glass}. From a set of tests where both single glazing and FCM data were available, we compared the two determinations of the exterior film coefficient, shown in Figure 2, and found excellent agreement. From this we concluded that the FCM alone may be used to determine the mean nighttime exterior film coefficient, and thereafter it was used as a standard part of the MoWiTT instrumentation.

RESULTS

This analysis included the nighttime winter data measured between November 1989 and March 1992. During this period, with the exception of a few weeks, the MoWiTT was in the west facing orientation. Because the prevailing wind was mainly from the west, there is a large amount of data in the windward hemisphere. The leeward data came from the relatively small number of tests when the MoWiTT faced east (Figure 3). The two-year duration of this study produced some high wind data despite the fact that the nighttime winter wind speed is typically low (between 0 and 2.2 m/s) at the Reno test site. We excluded the data when: (a) the absolute value

of the temperature difference (T_{glass} - T_{out}) between the exterior glass surface and the ambient was less than 2°C; (b) the exterior convective film coefficient was near zero (less than 0.1 $W/m^2 \cdot K$) or negative; (c) the absolute value of the temperature difference between the effective radiant and the ambient was less than 10°C; (d) when the wind speed was lower than 6.7 m/s and (T_{glass} - T_{out}) was less than 4°C. For these conditions, which occurred due to high ambient temperature or high exterior radiative temperature causing negligible convective heat transfer, the convective coefficient determination became unreliable due to the finite precision of the temperature and solar radiation measurements.

DISCUSSION

As shown in Figure 3, at zero wind speed the exterior convective film coefficient is non-zero and its value is presumably determined by natural convection. In the low wind speed region (0 m/s < wind speed < 2.2 m/s), h_{co} is still dominated by natural convection while above 2.2 m/s, the wind speed is the driving force.

As shown in Table 1, the average values of h_{co} are consistent within our measurement averages (estimated by the standard deviations) for all orientations in both windward and leeward hemispheres. We should note that the number of data points collected in each case and the average values of ΔT vary from one orientation to another and in some cases they are vastly different. This might explain why we see a higher average h_{co} in some orientations such as north-facing.

We also compared the widely-used models discussed in the introduction to our data. The results are shown in Figure 4.

THE ASHRAE/DOE-2 MODEL

The ASHRAE/DOE-2 model is based on Rowley's formulas which combine the convective and radiative heat transfer and define the exterior film coefficient for smooth and rough surfaces as:

for smooth surfaces $$h_o = 8.23 + 3.83V - .047\ V^2 \quad (1)$$

for rough surfaces $$h_o = 11.58 + 6.806V \quad (2)$$

where

V = wind speed in meters/second

The radiative heat transfer included in this formula is constant and is equal to 5.11 $W/m^2 \cdot K$ (0.9 $BTU/hr \cdot ft^2 \cdot F$).

In this case, we compared the MoWiTT's measured convective exterior film coefficient with the Rowley model. For this comparison, we subtracted the fixed radiative term from Equations 1 and

2 in order to obtain the ASHRAE/DOE-2 convective film coefficient. From the curves in Figure 4 for the "ASHRAE/DOE-2 smooth surface," it is obvious that this model is in disagreement with our data, especially in the high wind speed region. The disagreement becomes worse if one assumes (as is reasonable) that the window/building surface is not smooth, due to window detailing or rough facades, as can be seen from the higher-lying "rough surface" curve. Clearly Rowley's measurements and ours correspond to different physical situations in some essential way. Since our data applies to low-rise residences, it is expected that the significantly lower film coefficient we observe is more realistic than the one calculated by versions of DOE-2 using Rowley's formulas, and that conventional windows in fact perform better in low-rise buildings than the DOE-2 calculations indicate. Since the film coefficient becomes progressively less important for higher-resistance glazings, DOE-2 calculations should overestimate the energy savings from improved glazings in residences. This problem is remedied (Winkelmann, 1993), in the DOE-2.1E version which uses the MoWiTT model developed below.

THE KIMURA 6TH FLOOR MODEL

In the measurements by Ito and Kimura (1972), the convective and radiative terms were considered separately and measured independently. They performed the measurements on the outside surface of a six-story building. Their results for the sixth floor were later interpreted by Lokmanhekim as follows:

$$hco = 18.65\ (Vc).605 \tag{3}$$

V_c is the local wind speed in meters/second, calculated as following:
for the windward direction:

$$V_c = .25\ V \qquad V > 2\ \ m/s \tag{3-1}$$

$$V_c = .5 \qquad V <= 2\ \ m/s \tag{3-2}$$

for the leeward direction:

$$V_c = .3 + .05\ V \tag{3-3}$$

Figure 4 shows that the Kimura 6th floor model also disagrees with our data, although the disagreement is not as extreme as for the ASHRAE/DOE-2 model. Again, the disagreement is systematic, with the Kimura 6th floor model predicting a value significantly higher than we observe. Since this model is used to calculate the exterior film coefficient in the program WINDOW, care should be exercised in using the current or previous versions of that program to predict relative energy savings. The other problem with the Lokmanhekim formulation of the Kimura 6th floor model is that the formulas reduce to different constant values for the two hemispheres when the wind speed becomes negligible, leading to the nonsensical conclusion that one can distinguish between windward and leeward in the absence of wind.

THE KIMURA 4TH FLOOR MODEL

A different interpretation of the data by Ito and Kimura was given by Kimura (1977), who presents the following model for the exterior convective film coefficient:

$$h_{co} = 4.7 + 7.6U \tag{4}$$

where

U = local wind speed, measured at the window, in meters/second

This model is for a window installed between the third and forth floors of the six- story building. He presented the relationship between the local wind speed (U) and the wind speed on the roof of the building (V, in meters/second) as:

for the windward hemisphere $U = .2 + .24V$ (4-1)

for the leeward hemisphere $U = .2 + .064V$ (4-2)

These equations yield the following model for the film coefficient:

for the windward hemisphere $h_{co} = 6.22 + 1.824V$ (4-3)

for the leeward hemisphere $h_{co} = 6.22 + .4864V$ (4-4)

As shown in Figure 4, the MoWiTT and the Kimura 4th floor windward models yield approximately parallel curves, but Kimura's prediction is about 5 $W/m^2 \cdot K$ higher than the data. In the leeward hemisphere, the Kimura model is consistent with the small amount of medium and high wind speed data available, but disagrees with the more plentiful low wind speed data. However, we are not certain that this disagreement is significant. Comparisons of the low-wind-speed data between Figures 4-a and 4-b shows that the data in the leeward plot does not fall at the mean of the windward plot. We see similar shifts in data sets in other orientations of the MoWiTT, for which the statistics are poor. It is not clear whether these shifts are statistical or mask some undetermined systematic error in our measurement. In any case we cannot say that the Kimura 4th floor model and our leeward data are necessarily mutually inconsistent. Nevertheless, there is a clear trend in the three models that makes some physical sense. In the ASHRAE application of the Rowley measurements, the local free-stream wind speed (e.g., at several centimeters from the window) is taken to be equal to the wind speed measured at a weather tower. One might expect that if this situation ever occurs it should be in a high rise relatively isolated building and on sides other than leeward. The Ito and Kimura data indicate that at the 6th floor the correlation between local and weather-tower wind speed is weak, and that it is still weaker at the 4th floor level. For the MoWiTT data, which is essentially at ground level (2 meters height), the correlation is still weaker. This progression indicates that height must be a significant parameter in determining the exterior film coefficient, and suggests that it may be possible to formulate a height-dependent model which includes all of the data in a consistent way. We have not as yet attempted to formulate such a model.

A FILM COEFFICIENT MODEL FOR LOW-RISE BUILDINGS

Since, as Figure 4 indicates, none of the commonly-used models is in very good agreement with our data, we have constructed yet another semiemperical model, which we refer to as the "MoWiTT model." This model should be more realistic for low-rise buildings than those discussed above.

As noted above, low wind speeds as measured at a 10-meter height characterized much of our data. This also characterizes many of the places people prefer to live, either because of prior selection of location or the shielding effects of terrain, other buildings, or vegetation. Accordingly, we cannot neglect the effect of the temperature-driven natural convection. We assumed fully developed turbulence, spatially uniform surface temperatures, and a spatially uniform average film coefficient. Following studies by Lorenz (1881), King (1932), and McAdams (1954), we represented this turbulent natural convection by a term in the form:

$$h_{co(natural)} = C_t\,(\Delta T)^{1/3} \tag{5}$$

where

C_t = Turbulent natural convection constant

ΔT = Temperature difference between the exterior glass and the ambient

In fact, a form with the 1/4 exponent characteristic of laminar natural convection also fits the data, but was considered less realistic than Equation 5 on physical grounds (Gebhart 1973).

For forced convection we used the conventional form:

$$h_{co(forced)} = aV^b \tag{6}$$

where

a and b = constants
V = free stream wind speed at a 10-meter height

We tried a number of methods of including a dependence on wind direction into the model, but were unable to find one that was significantly better than a single division of the data into windward and leeward hemispheres based on the wind direction at the weather tower relative to the normal to the window, and the separate analysis of the two data sets, as was also done by Ito and Kimura (1972).

MOWITT MODEL

Because the transition region between natural and forced convection is poorly understood, there is no theoretical basis for combining natural and forced convection beyond the expectation that

the film coefficient should vary continuously between the two regions. We use a simple model, combining Equations 5 and 6, which includes components of natural and forced convections in such a way that the effect of each component, in its region, dominates the h_{co} calculation:

$$h_{co} = \sqrt{[\, C_t(\Delta T)^{1/3} \,]^2 + [\, aV^b \,]^2} \tag{7}$$

We estimated the values of the constants in Equation 7, C_t, a, and b, by fitting this model to the MoWiTT data using a computer program based on standard statistical techniques (Press, et al., 1986). We fit the model to windward and leeward data separately. Similar to previous studies, we cannot distinguish beyond a windward/leeward dependence. This could be due to the difference between tower and local wind direction (site-scale turbulence), or to the fact that the 10-minute averaging of the data may wash out the rapid fluctuations of the wind. We note that at zero wind speed the MoWiTT model is the same for windward and leeward data, as must be true physically, a property that is not shared by the ASHRAE model.

We did a general fit of the MoWiTT model (Equation 7) in the windward direction, where most of our data is collected. Since theoretically the natural convection, unlike the forced convection, does not depend on the direction of the wind, we used the constant C_t for the natural convection term determined from the windward data as a fixed parameter in the leeward model; the fit then determined the values of the wind-dependent parameters. The values of the constants resulting from the fits are given in Table 2. These were then used to calculate the "MoWiTT model" curves in Figure 4 which shows plots of the measured and the calculated h_{co} against the wind speed for the west-facing windward and east-facing leeward data. In order to display the calculated h_{co} (which is a function of two variables) as a curve in the graph, the weak ΔT dependence was suppressed by using the average values of ΔT in Equation 7 for each data set, rather than the measured ΔT at each point. Also indicated in Table 2 are the RMS values which represent the scatter of data around the curves. The uncertainty estimate in the h_{co} values due to the experimental error in determining the radiative flux is 4%, which is in reasonable agreement with the observed RMS.

We also calculated the average and the standard deviation of h_{co} for all orientations in both the windward and the leeward hemispheres for the natural convection region where the wind speed is between 0 and 2.2 m/s (Table 1).

CONCLUSION

The previous studies in estimating the exterior film coefficient have been based on laboratory measurements, wind tunnel measurements, computer simulations, or measurements on a medium-rise building. There is a great deal of ambiguity and disagreement among these studies, as well as a good deal of inconsistency in their application (most notably in the definition of free-stream wind speed). At the MoWiTT facility, we measured the exterior convective film coefficient for a low-rise structure under realistic conditions. We believe that our measured data present a physically reasonable model which will be useful in modeling the heat transfer through windows, particularly in residential buildings.

Our measurements indicate that the ASHRAE methodology for calculating a "standard" convective film coefficient is incorrect for a low-rise building because it assumes a 6.7 m/s (15 mile/hour) local wind, a highly unlikely occurrence for a low-rise construction. All of the commonly used exterior film coefficient models disagree with our data. All are based on data measured for, or assumptions appropriate to, high or medium-rise buildings. Our data confirm and extend a trend in previous formulas toward lower film coefficient and weaker wind dependence at decreasing height.

Our measurements are being incorporated into the latest version of DOE-2 (version 2.1E), and will be incorporated into a future version of WINDOW. We believe that for low-rise buildings this will allow for more accurate prediction of outdoor U-values, contributing to a more precise calculation of window energy usage in residential buildings and providing better information for developing window energy ratings.

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APPENDIX A

Calculation of Exterior Convective Film Coefficient

The nighttime heat balance at the exterior surface of a window is a combination of convection from the surface to the ambient and radiation emitted from the surface and received from the sky and ground viewed by the window. It can be expressed as the following equations:

$$Q_{net} = h_o A (T_{out} - T_{glass}) \quad \text{(A-1)}$$

$$Q_{net} = Q_{rad} + Q_{conv} \quad \text{(A-2)}$$

$$Q_{rad} = A \varepsilon [I_s - \sigma (T_{glass} - T_{kelv})^4] \quad \text{(A-3)}$$

$$Q_{conv} = h_{co} A (T_{out} - T_{glass}) \quad \text{(A-4)}$$

$$h_{co} = (Q_{net} - Q_{rad}) / A(T_{out} - T_{glass}) \quad \text{(A-5)}$$

$$h_{co} = \{Q_{net} - A \varepsilon [I_s - \sigma (T_{glass} - T_{kelv})^4]\} / A(T_{out} - T_{glass}) \quad \text{(A-6)}$$

where

Q_{net} = net heat flow through single glazing surface	[W]
Q_{rad} = radiative heat flow through single glazing surface	[W]
Q_{conv} = convective heat flow through the single glazing surface	[W]
I_R = thermal infrared radiant flux incident on window from sky/window hemisphere	[W/m^2]
ε = glass emissivity	(0.84)
σ = stefan-Boltzman constant (5.67×10^{-8})	[$W/m^2 \cdot K^4$]
T_{out} = Ambient Temperature	[°C]
A = Window sample area	[m^2]
h_o = effective exterior film coefficient	[$W/m^2 \cdot C$]
h_{co} = exterior convective film coefficient	[$W/m^2 \cdot C$]
T_{kelv} = temperature of absolute zero (-273.15)	[°C]
T_{glass} = exterior glass temperature	[°C]

APPENDIX B

A Description of the Film Coefficient Meter

The effective exterior film coefficient is measured in the MoWiTT by means of a "film coefficient meter" consisting of a sheet of glass backed by a heated metal plate. Between the plate (which is held at a constant temperature) and the glass is a thin layer of material matched in thermal conductance to several small commercially-available heat flow sensors that measure the heat flow rate to the glass. The entire unit is insulated around the edges and behind the heated plate. It is mounted on the MoWiTT exterior wall between the two test chamber openings. The film coefficient meter is approximately one foot wide, and is the same height as the test window. Heat flow measurements are made along the meter's vertical centerline. Infrared photographs have verified that there are no horizontal temperature gradients in the central part of the glass, where the film coefficient measurement is made. Figure B-1 shows a schematic drawing of the film coefficient meter.

TABLE 1
The average and the standard deviation of the exterior convective film coefficient for wind speed between 0. and 2.2 m/s (0. and 5.0 miles/hour)

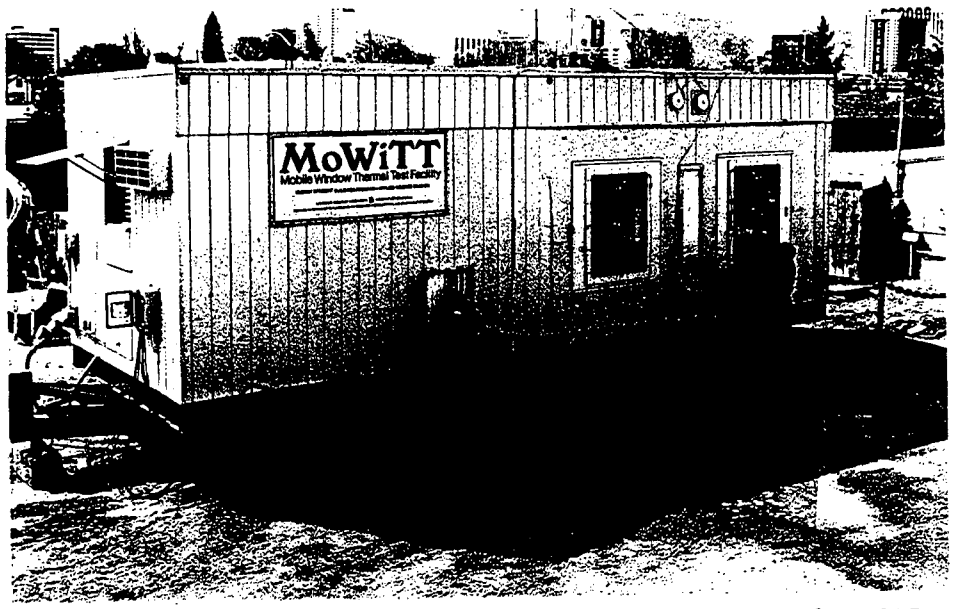
Wind direction	MoWiTT orientation	No. of data points	$\langle T_{glass} - T_{out} \rangle$		$\langle h_{co} \rangle$		Standard deviation	
			F	°C	BTU/hr·ft^2·F	W/m^2·K	BTU/hr·ft^2·F	W/m^2·K
Windward	North-facing	377	65.80	18.78	0.89	5.05	0.20	1.14
Windward	South-facing	139	104.40	40.25	0.73	4.16	0.08	0.45
Windward	East-facing	44	99.50	37.51	0.79	4.49	0.11	0.62
Windward	West-facing	2726	62.30	16.82	0.56	3.21	0.19	1.07
Leeward	North-facing	559	63.62	17.55	0.87	4.93	0.18	1.01
Leeward	South-facing	119	106.34	41.30	0.70	3.98	0.07	0.40
Leeward	East-facing	85	103.10	39.50	0.70	3.98	0.07	0.38
Leeward	West-facing	1238	59.45	15.25	0.50	2.83	0.16	0.91

TABLE 2
The results of fitting the MoWiTT/FCM data to the model:

$$h_\infty = \sqrt{[\,C_t(\Delta T)^{1/3}\,]^2 + [\,aV^b\,]^2}$$

Wind Direction	C_t	a	b	rms
Metric Units	$W/m^2 \cdot K^{4/3}$	$W/m^2 \cdot K \cdot (m/s)^b$	–	$W/m^2 \cdot K$
windward	0.84 ± 0.015	2.38 ± 0.036	0.89 ± 0.009	0.91
Leeward	0.84	2.86 ± 0.098	0.617 ± 0.017	0.76
English Units	$BTU/hr \cdot ft^2 \cdot F^{4/3}$	$BTU/hr \cdot ft^2 \cdot F.(MPH)^b$	–	$BTU/hr/ft^2 \cdot F$
windward	0.096 ± 0.0004	0.203 ± 0.005	0.89 ± 0.01	0.16
Leeward	0.096	0.335 ± 0.016	0.59 ± 0.017	0.134

(a)



CBB 923-3485

(b)

CBB 905-4486

Figure 1: The Mobile Window Thermal Test (MoWiTT) facility. (a) Overall view of the facility in north-facing orientation, showing the two calorimeter window samples, the on-site weather tower, and the FCM. Downtown Reno, NV. is in the background. (b) A close-up of the calorimeter sample openings and the FCM (center), also shown at top center is the IR pyrogeometer (left) and a companion pyranometer (right).

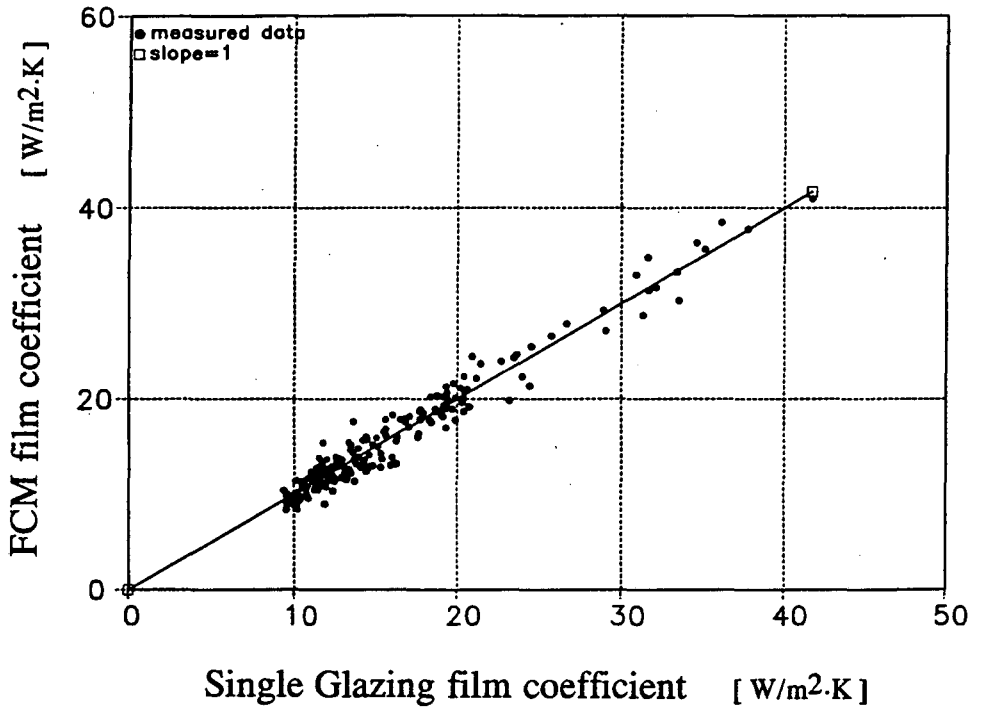
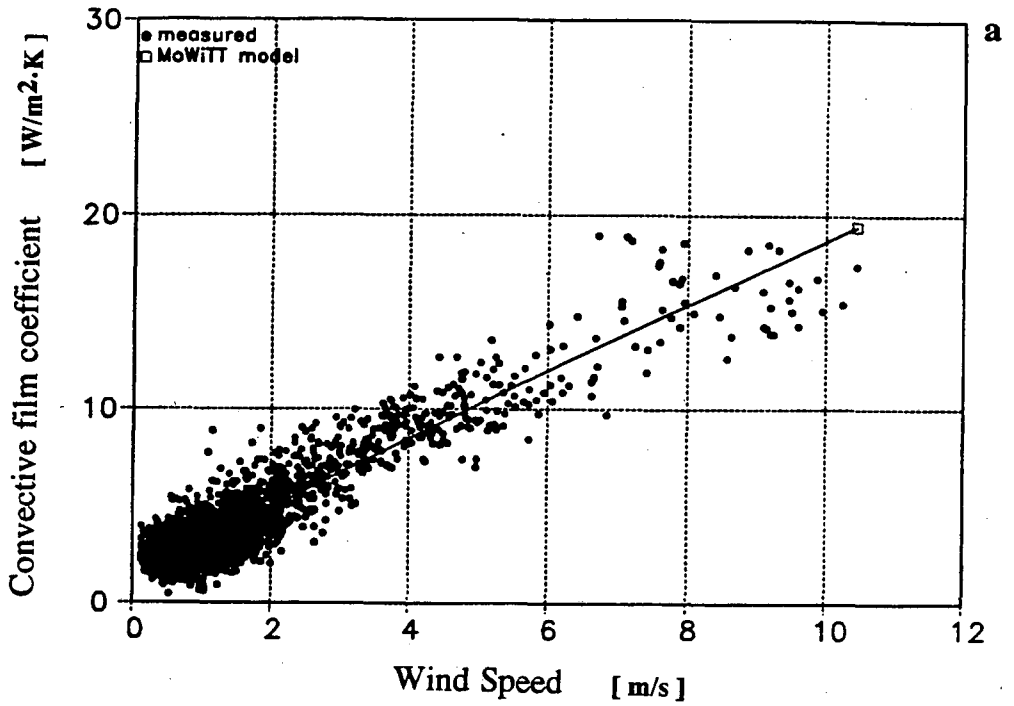


Figure 2: Exterior convective film coefficient; film coefficient meter vs. single glazing measurements



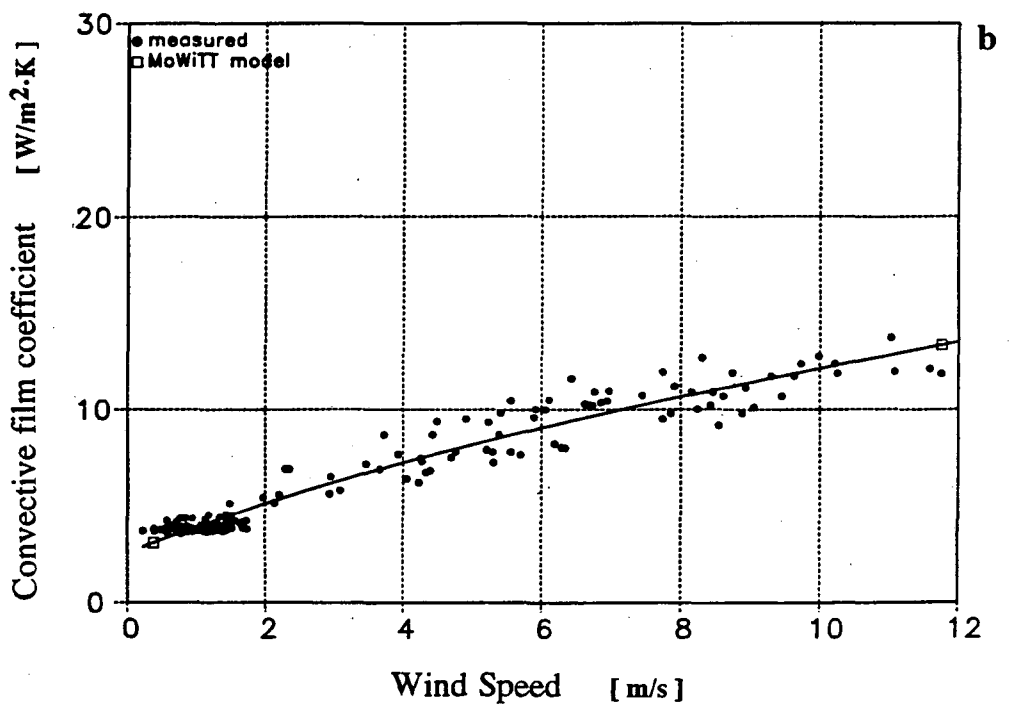


Figure 3: Exterior film coefficient vs. wind speed (measured at 10-meter height, on site): (a) windward, (b) leeward

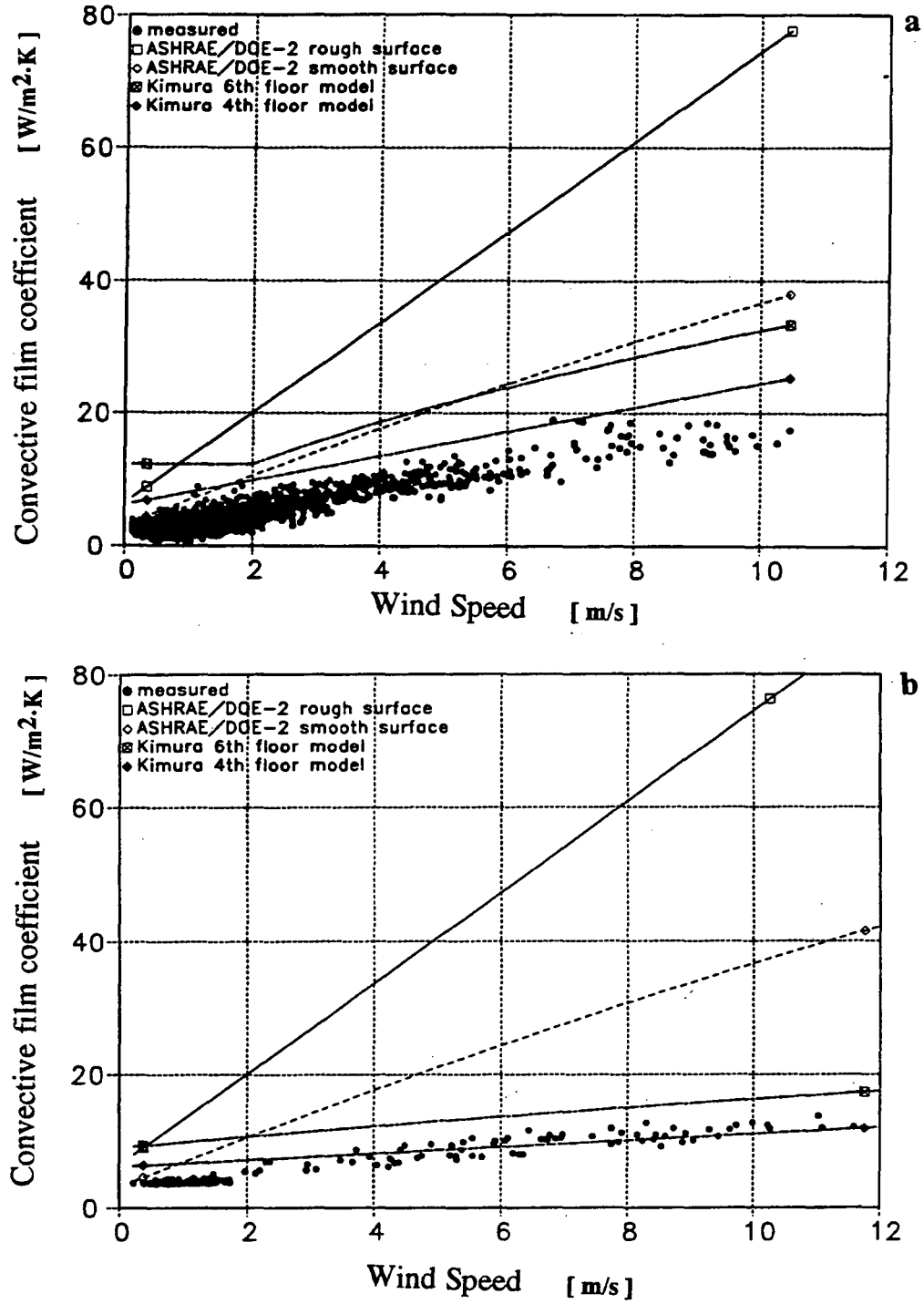


Figure 4: Exterior film coefficient vs. wind speed (measured at 10-meter height, on site): (a)-windward , (b)-leeward

Exterior Film Coefficient Meter

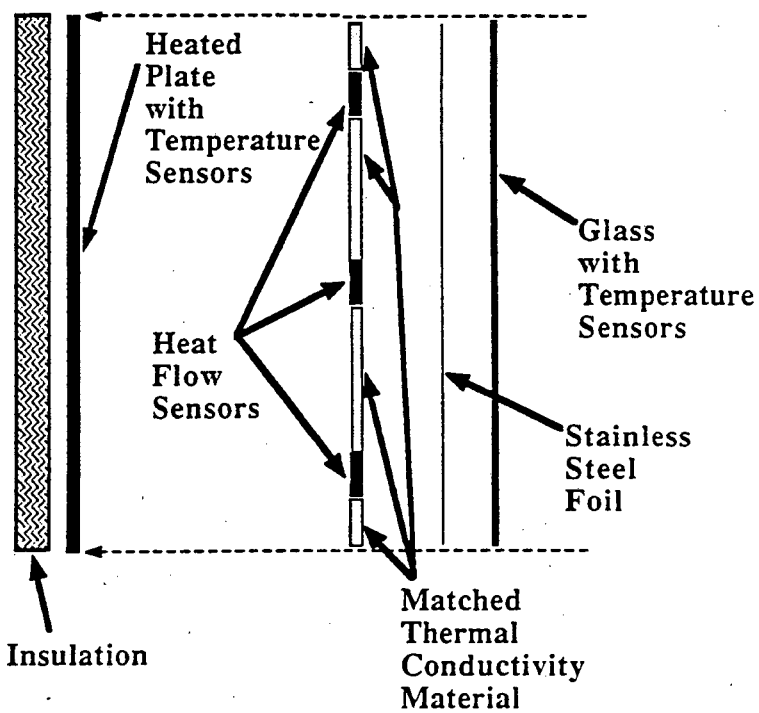


Figure B-1: Schematic drawing of the film coefficient meter

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