THE USE OF THE WIND TUNNEL IN THE ANALISIS OF NATURALLY VENTILATED STRUCTURES

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CLASSIFICATION OF AIR MOTION SYSTEMS AND PATTERNS

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ABSTRACT

Periodically, experiments have been conducted at research establishments to understand airflow behavior and to record wind patterns. Most of this work investigates lateral motion and the information is scattered. Furthermore, vertical air motion in buildings, although used for centuries, is not clearly defined. This paper is a factual record of completed work from reliable sources through a graphical vocabulary of typical wind patterns in and around buildings. An introduction is given to problems accompanying high velocity winds.

1. INTRODUCTION

Pressure differences, between any two points, results in air motion. This may be at a global scale, where prevailing directions are invariably constant with desirable velocities, or at a local scale governed by land-water (Fig. 1) or topographic (Fig. 2) relationships. To establish design indicators it is relevant to determine the human needs for airflow under varying conditions (Fig. 3). The horizontal transport of an air mass is a consequence of large scale differences in air pressure. This horizontal pressure "gradient wind" can only be observed in its undisturbed state at upper atmospheric levels. The earth's surface acts as a brake on the velocity, a factor of considerable importance on the layer near the ground. Wind speed, therefore, is a function of height (Fig. 4). Air will flow in a laminated manner, unless it is disturbed, causing separation and turbulence (Fig. 5).

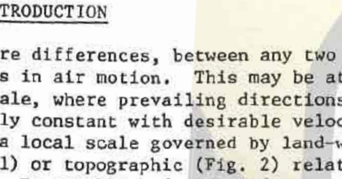

Fig. 1a - Morning Anabatic Flow, Sea-breeze

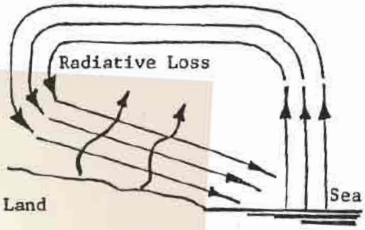

Fig. 1b - Evening Katabatic Flow, Land-breeze.

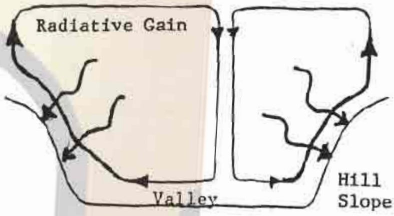

Fig. 2a - Morning Anabatic Flow, Uphill

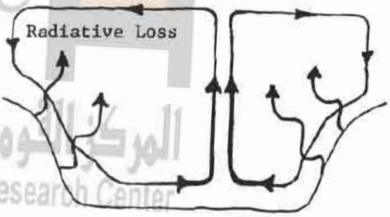

Fig. 2b - Evening Katabatic Flow, Downhill

2. AIRFLOW BEHAVIOR AND PATTERNS

Wind flowing perpendicular to a cube, decreases in velocity when it reaches its face. High pressure zones are formed on the windward side, pushing air around the sides and up over the top. A portion is, however, diverted downward creating an eddy at the windward base of the structure. This windward eddy will

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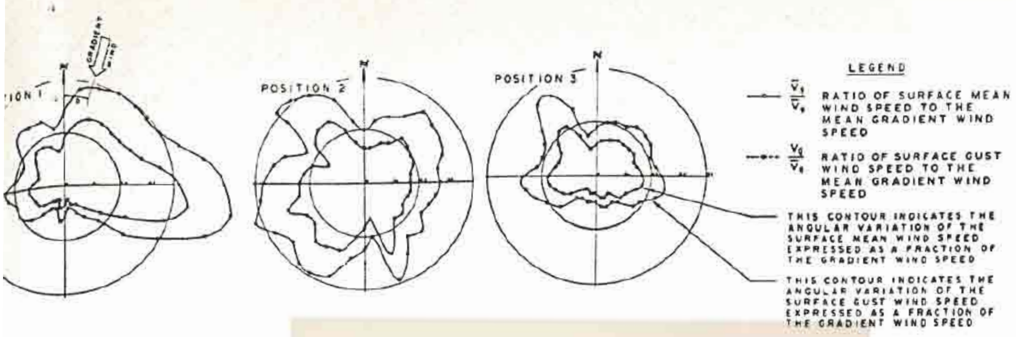
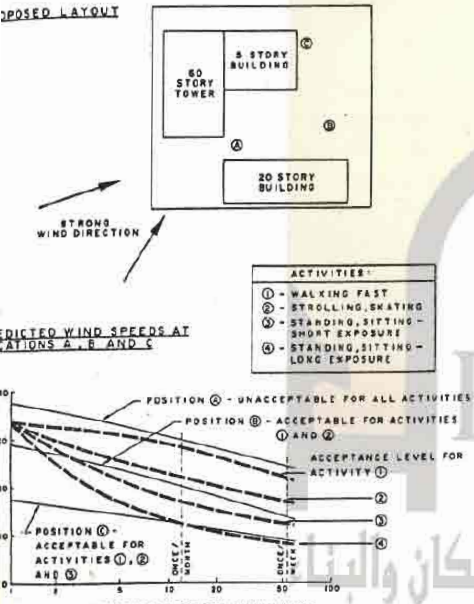


Fig. 18 Typical Variations of Surface Wind Speeds (Mean and Gust) from Different Azimuth Angles [After Isyumov$^{(18)}$]



20 The Evaluation of the Ground Level Wind Conditions at Three Points Near a 60 Storey Tower [After Isyumov$^{(18)}$]

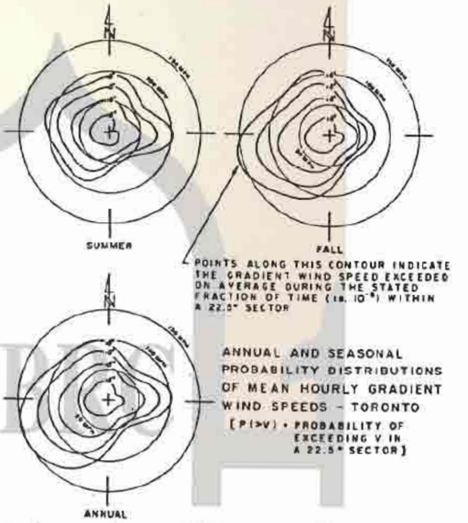


Fig. 19 Annual and Seasonal Probability Distributions of Gradients Wind Speed [After Isyumov$^{(18)}$]

been published in a form which is not suited to ilation problems. The study described in reference volved tens of thousands of measurements of mean sures on a variety of low-rise building forms in dif- nt terrains and for varying wind directions, but the ished data is concerned almost exclusively with imum values. The original observations have been ived in a computer compatible form but have not published. The situation is similar in regard to most of the data collected in the many studies of cladding loads on tall buildings. Most wind loading codes quote pressure distributions for design purposes but, again, these are usually maximum values and are not suited to the computation of flow rates.

Data collected prior to the 1960's, such as the extensive work of Chien et al$^{(19)}$, was commonly derived from tests in smooth uniform flow and must be viewed with suspicion. The work of Jensen and Franck$^{(7)}$ contains useful data for a variety of elementary isolated building shapes. Data concerning the distribution of wind pressure on buildings in the presence of numerous other structures of similar proportions (e.g. a typical

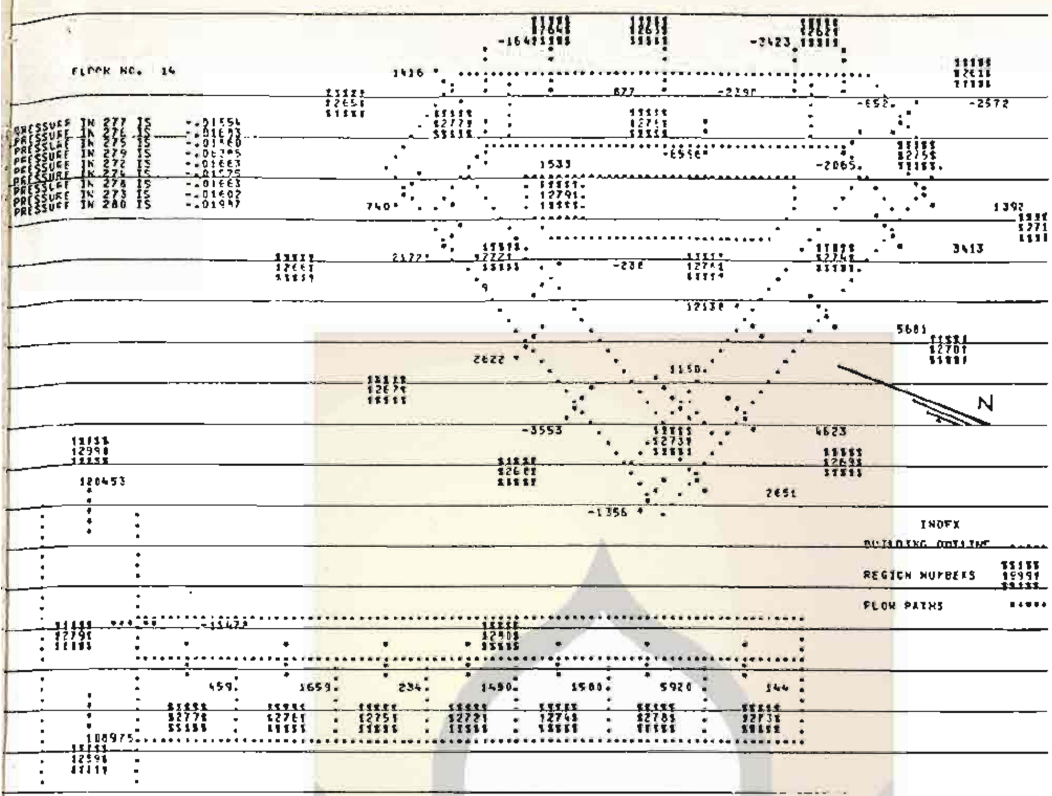


Fig. 15 Distribution of Internal Flows and Pressures at Floor 14 for ΔT = 5°F, V = 17 mph N, Fan Flow = 23 x 11,400 CFM

gradient speed exceeds some value V_G, has a direction in the range θ to $\theta + d\theta$ and the external temperature lies within the lower and upper limits, T_L and T_u. If the relationship, $Q(V_G, \theta)$, is re-written as $V_G(Q, \theta)$, the speed required from direction θ to achieve a flow rate Q, then the probability that the flow rate exceeds Q is given by;

$$P(>Q) = \int^{2\pi} P(V_G(Q, \theta), \theta | T_L < T < T_u)\, d\theta$$

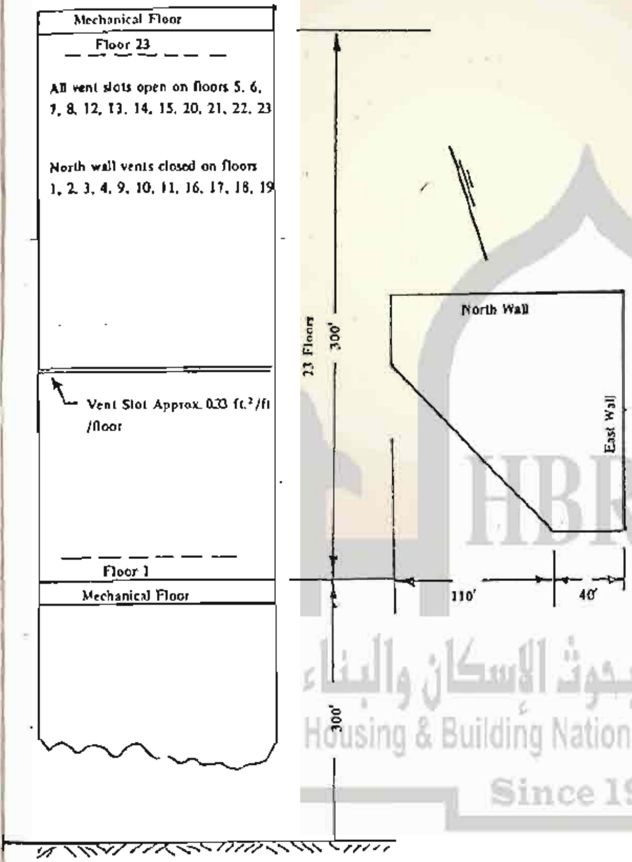
and the number of hours per year, N_Q, for which this flow rate will be achieved while the external temperature is within the acceptable bounds is simply $N_Q = 8760\, P(> Q)$. Provided that the climatic data and the wind tunnel data are in a computer compatible form then computations of the type outlined above are readily made. It is not suggested that the question posed above is sufficient to permit an evaluation of a proposed ventilation scheme relying, in part, on wind induced flows but other questions can be approached in a similar manner and quantitative results obtained.

TABLE 1: FLOW RATES AT FLOOR 13 FOR VARIOUS FORCING CONDITIONS

Forcing Conditions			Inflow Through Slots	Outflow Through Slots	Flow to Vertical Vent
Temp.*	Wind**	Fan***	CFM	CFM	CFM
5°F	0	11,400	11,150	0	11,150
5°F	0	0	0	2,000	– 2,000
10°F	0	11,400	10,700	0	10,700
10°F	0	0	0	2,800	– 2,800
5°F	17N	11,400	25,600	14,100	11,500
5°F	17N	0	19,400	19,500	– 60
5°F	35N	11,400	45,600	32,900	12,700
5°F	35N	0	39,900	37,100	2,800

* $T_e - T_i$
** Gradient speed in mph
*** Fan flow as an average per floor (CFM)

oints for each of 36 wind directions. For the purposes of f the mathematical model these measurements were sed to define the external pressure in 782 zones with 7 circumferential zones per floor. Because of the ature of the ventilation system it was possible to analyse he building in two stages with the upper and lower 23 floors loors being examined separately. At each floor the in- rnal structural was modelled as seven office areas, a eiling plenum and a section of the main vertical ventila- ion duct. For the upper 23 floors this model involved 07 internal regions and 391 external regions, the latter vith specified pressures.



g. 13 Approximate Dimensions of Building

ternal flows were computed for

) two wind speeds (V_G = 17 mph and 35 mph)

) two temperature differences ($T_i - T_e$ = $5°F$ and $10°F$)

(iii) three wind directions, and

(iv) three fan operating conditions.

The wind speeds (V_G) are mean hourly values of the gradient wind speed and correspond to probabilities of exceedence of 50% and 10% respectively. The nature of the output from the computer program is shown in Figs. 14 and 15 which show the flow distributions at floor 14 for the following conditions;

Fig. 14: V_G = *17 mph* from North
$T_i - T_e$ = $5°F$
No forced flow.

Fig. 15: V_G = *17 mph* from North
$T_i - T_e$ = $5°F$
Exhaust fan at top of ventilation shaft produces a fixed flow of 23 x 11,400 CFM.

The flow rates shown in Figs. 14 and 15 are CFM and the sign is such that a flow (Q_{ij}) from region i to region j is positive if $j > i$. The pressure distribution is given in inches of water. Since this floor is roughly midway in the upper section the "stack effect" flow into the vertical shaft is small when the fan is inoperative but the external pressure distribution produces a cross-flow of about 19,000 CFM.

Computed flows into the vertical ventilation shaft are shown in Fig. 16, the group of curves marked "free" represent the flows with the fan inoperative and those marked "forced" show the flows when the exhaust fan is operating at 23 x 11,400 CFM. The marked increase of flow with height in the case of the forced flows is due to the pressure drop in the shaft and the fact that the duct characteristics for each floor were assumed to be identical, i.e. no attempt was made to balance the flow per floor by choking the ducts from the upper levels. The "cyclic" variation with height is due to the assumed configuration (shown in Fig. 12) in which the north-wall vents are closed on about half of the building. The flow distributions at floor 14 for other conditions are summarised in Table 1. The variation also by Givoni[17]. In addition, both these works contain extensive references.

Apart from comparatively small, simple structures, the most promising method of evaluating internal flows is a hybrid technique employing a physical model to determine the external pressure distribution and a mathematical model of the interior. Pressures determined from wind tunnel tests do not include those components due to "stack effects" and, for high-rise structures, these are of significance. The inclusion of stack effects is, however, quite simple and the external pressure is given by;

$$P_e = P_{ew} - \Delta\gamma \cdot z$$

where $P_{ew} = C_p \, ½\rho \bar{V}_R{}^2$

where C_p = pressure coefficient determined from wind tunnel testing
V_R = a suitable reference wind speed
ρ = air density
z = height above ground
$\Delta\gamma = \gamma_e - \gamma_i$
γ_e = specific weight of external air
γ_i = specific weight of internal air
$\Delta\gamma \simeq \dfrac{T_i - T_e}{7000}$ lb/ft³
T_e = external temperature (°F)
T_i = internal pressure (°F)

A technique employing external pressure coefficients measured on solid models can be employed to compute nternal flows only if the flow through the structure does not disturb the flow field. This will be the case if he porosity of the walls does not exceed about 10% to 0%. At higher porosities, flow through the structure will modify the external pressures and flow rates comuted from "solid model" pressure coefficients will be verestimated. In high-rise structures however, it is nlikely that wall porosities would approach the above mit.

he following section outlines a mathematical modelling echnique while Section 5 describes a case study in hich the hybrid approach was employed to examine e internal flows in a 600 ft. building incorporating ntilation slots which produced a wall porosity of the der of 2½% .

4. MATHEMATICAL MODELLING OF INTERNAL FLOWS

The computation of the internal flows induced by the external wind induced pressures and the pressures induced by temperature differences cannot, except for the most simple cases, be accomplished by hand. The computational procedures are, however, well established and involve the solution of a set of non-linear algebraic equations. The development of a mathematical model of the problem is now outlined;

(i) the exterior surfaces of the building are divided into a selected number of regions the size of which will be determined primarily by the magnitude of the pressure gradients on the face. For a multistorey building this will normally require about four subdivisions per floor for each face of the structure, with additional regions on the roof if this is vented. The mean external pressure in each of these regions will be denoted by P_I, $I = 1, 2 \ldots N_e$ where N_e is the number of external regions.

(ii) the interior of the building is divided into regions which might include, for example, the major office areas, the ceiling plenum, the main vertical duct, and leakage paths offered by elevator shafts, stairwells and pipe ducts. The mean pressures within these regions will be denoted by P_i, $i = 1, 2 \ldots N_i$, where N_i is the number of internal regions.

(iii) The flow characteristics of the connections between regions are defined by relationships of the form;

$$Q_{ij} = C_{ij} |P_i - P_j|^M \frac{(P_i - P_j)}{|P_i - P_j|}$$

where Q_{ij} is the flow from region i to region j. The coefficient C_{ij} and the exponent M are properties of the physical connection between regions i and j. For ventilation as opposed to infiltration the connections will generally be sufficiently large to ensure that the flow is virtually independent of Reynolds Number and hence,

$$M = ½$$

and $C_{ij} = C_d A_o \sqrt{\dfrac{2}{\rho}}$

where A_o = area of connection
C_d = a discharge coefficient