Dynamic Interpane Systems for Multipane Solar Collector Windows

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ABSTRACT

It has been shown previously that for twin-pane windows, a variety of interpane blinds and/or other interpane structures can be employed to suppress natural convective and unwanted (infrared) radiative heat losses from a wintertime conditioned space to its cold exterior. For previously reported systems, effective R-values greater than $1.06 m^2 \cdot {}^oC/W$ (or $6[Btu/hr \cdot ft^2 \cdot {}^oF]^{-1}$ have been measured for solar acceptance mode operation and R-values greater than $1.76 m^2 \cdot {}^oC/W$ (or $10[Btu/hr \cdot ft^2 \cdot {}^oF]^{-1}$) have been measured for nighttime mode operation. New dynamic interpane systems have been investigated which utilize previously considered methods as well as forced convective flows, together with principles of regenerative heat exchange to suppress further the undesirable heat losses from a conditioned space. Design principles for such windows are discussed.

KEY WORDS

Aspirating windows, insulating windows, hybrid solar collector, multipane solar windows.

INTRODUCTION

It is well known that the thermal resistance of a building's non-transparent thermal barrier can be increased, as desired, through a broad variety of insulating techniques. Such easily accessible methods have not been the case for window systems. Accordingly, it is common to find the thermal resistance of a window system to be an order of magnitude smaller than that of a well-insulated wall[1]. A number of studies have shown how to increase the thermal resistance of a window system through the passive suppression of natural convective and infrared radiative processes [2-4].

It is also well known that increasing the multiplicity of window panes increases the thermal resistance of a window system. The desirability of the greater multiplicity feature is frequently outweighed by the necessary increase in window costs (per unit area) as well as the necessary decrease in the window's transmittance to both diffuse and to direct solar radiation[3-5]. Part of the decrease of transmittance with increasing pane multiplicity is accounted for by the net reflection losses at the initially incident surface. Another part of the decrease of transmittance with increasing pane multiplicity derives from the increasing interpane thermalization of solar flux. The interpane thermalization of solar flux in a multipane window (effective absorbtivity heating) means that the interpane regime may display high temperatures. The effective absorbtivity of a window system increases with pane multiplicity. High window absorbtivity generally implies enhanced heat losses to the cold exterior.

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Thus, as a passive solar collector, the efficiency of a window system generally decreases as the pane multiplicity increases.

It is well known that the above noted generalization for a "passive" solar collector is not appropriate for an "active" collector[6]. There it is generally found that collector efficiency is a function of the mass flow rate (of collector coolant) and that all efficiencies (regardless of cover plate multiplicity) decrease as effluent temperature increases[7]. Thus, for relatively "low" effluent temperatures, efficiencies for one, two, or three cover plates are all high. For the lowest effluent temperatures, the single plate is best. At somewhat higher effluent temperature, the efficiency of the single cover plate is surpassed by that of the double plate collector. At still higher effluent temperature, the efficiency of the double plate collector is surpassed by that of the triple plate collector[6]. And so on.

What can be said, then of the performance of a window system that is a hybrid? A direct gain device (window) that may, for example, also operate as an active counter-flow heat exchanger, a supplier of air for ventilation (or other purposes), a suppressor of unwanted natural convective and infrared radiative transport, an inhibitor of conductive heat losses, and a heat recovery unit for the interpane enthalpy which is deposited by the solar absorbtivity of a multipane window. Performance expectations for such a window system are discussed next.

DESIGN CONSIDERATIONS:

Consider the side view of a three-pane aspirating window (Figure 1). It is assumed that the window is to be operated during the winter heating season and that the two interpane separations, δ_1 and δ_2 need not be identical. Inlet air at the low temperature, T_A, is introduced into the exterior channel (channel 1) with a mass flow rate $\dot{m}_A$. If the Reynolds number for channel flow in downward (channel 1) or upward (channel 2) flow is large enough, the gravitationally induced free convective recirculation is suppressed and the heat transfer processes are largely independent of natural convective processes. In order to maintain the lowest net heat transfer rates in the negative-x direction, it is desirable to assure non-turbulent flow in both channels. Where $\dot{m}_A = \dot{m}_B$, the two Reynolds numbers are equal, $Re_1 = Re_2$

Interpane blind-like structures have been used previously[4] to suppress both infrared radiative and natural convective energy transport. For an aspirating window system, such interpane blinds also serve as Reynolds number suppressors. For the flow characteristics noted in Figure (1), vertically oriented blinds may be employed. Such an arrangement is shown in Figure (2). Given the system illustrated in Figures (1) and (2), the three-pane aspirating system has the following features:

(1) It is a regenerative heat exchanger whose cold boundary heat loss is given by

$$\dot{q}_A'' A = \alpha^* A + \dot{q}_B'' A - \dot{m} c_p (T_B - T_A) \qquad (1)$$

Here $(\dot{q}_B'' A)$ is the window's heat gain rate at the warm boundary; (A) is the window area; α^* is the effective window heating per unit area due to the solar absorbtivity; (c_p) is the specific heat of air: $(\dot{m})$ is the mass flow rate of air; and$(T_B - T_A)$ is the temperature difference between the window's warm and cold boundaries.

Interestingly enough, if $\dot{m} = 0$ and α^* is sufficiently large, $\dot{q}_B''$ may be less than zero---corresponding to a net solar absorptance which heats both the building exterior and the building interior. For the case where $\dot{m} >> 0$, the calculations given in reference (8) show that the regenerative heat exchanger feature assures that higher multiplicities of panes correspond to higher thermal flushing efficiencies (and lower values of $\dot{q}_A''$)

(2) It is a laminar flow, regenerative heat exchanger. This laminar flow can be assured by the selection of the interpane separations, δ_1 and δ_2, as well as by the interblind spacing, S. Vertical flow systems (as shown) may employ vertical blinds. Horizontal flow systems may employ horizontally oriented blinds.

(3) It is a beam daylighting window system, operable by use of low emissivity blinds.

(4) In the solar acceptance mode it is an infrared radiative suppression window device. The suppression of infrared losses between the warm boundary and the cold boundary derive from two features.

(a) the highly reflective interpane blinds[4].

(b) the multiplicity of infrared absorbing panes.

By far, benefits derivable from (a) are more important.

(5) In the nighttime mode, with $\dot{m} = 0$, with the blinds closed to define four low infrared emissivity air spaces, the three pane system is found to have the thermal resistance of a well insulated wall. An R-value $\geq 2.64 m^2 {}^\circ C/W$ (or ≥ 15 $ft^2 hr. {}^\circ F/Btu$) is found using the methods of references (4) and (9). This very low nighttime R-value is found even though free convective effects are not significantly suppressed with the blinds closed and with $\dot{m} = 0$.

(6) A nighttime mode under current study is that for which ($\dot{m}$) is very small ($\dot{m} \gtrsim 0$) and for which the blinds are closed. Laminar flow, free of recirculatory free convective effects are expected to suppress $\dot{q}_A''$ below that observed for the case of item (5), above.

(7) It is a (reverse) counterflow heat exchanger and thermal flushing device for summer use. If the direction of flow is reversed, during summer time, then thermally loaded, to-be-discarded interior air can be used to inhibit heat transfer rates, $\dot{q}_B''$. There are a number of commercially available aspirating windows which operate as thermal flushing devices during summer operation.

(8) For $\dot{m} = 0$, it is a fine summertime shading device[4,9,11].

STABILITY OF FLOW

There are several questions regarding flow stability raised by a design of the kind considered herein. First, what criteria for non-reversal of flow (due to free convective processes) are there? Although the boundary conditions used by Rao and Morris[10] are slightly different from ours, their results indicate that adequately large flow rates and small Rayleigh numbers can assure non-reversal of flow (Figure 3). In Figure (3), (η) is a dimensionless temperature; (Re) is the Reynolds number; and (Y) is the dimensionless space variable in the interpane air space. Inasmuch as we can assure[11] adequately small Rayleigh numbers by the selection of S (interblind spacing), these criteria can be assured. Interblind spacings of the order of 1 centimeter give Rayleigh numbers substantially less than 1,000. But Rayleigh numbers greater than 1,000 also correspond to NO FLOW REVERSAL if the flow rates are adequate. For cooled upward flow reference (10) shows no flow reversal effects (Figure 4). The case under study here corresponds to heating at one wall and cooling at the other. It is our current conclusion, then, that the constraints of Figure (3) represent a "worst possible case" and that flow reversal can be avoided in the generic class of devices under discussion.

Another question of flow stability derives from the possible onset of turbulence (for Reynolds numbers substantially greater than some 10^3). Given adequate forced flow velocities needed to prevent flow reversal, the proper selection of (δ) and (S) can be made to assure laminar flow. Similar results are deducible from the work of Sherwin and Wallis[12,13].

THE EFFECTIVE WINDOW ABSORBTIVITY

The transmissivity of a solar collector window is degraded by the inclusion of interpane solid surfaces (blinds). This is true even where the surfaces are favorably aligned and are highly reflective to solar radiation. Significant portions of this degraded transmissivity then serve to enhance the effective absorbtivity, α^*, of the solar collector window. It is expected that (α^*) is almost entirely recoverable, where $\dot{m} >> 0$. For previously studied windows , $\dot{m} = 0$ and α^* is partially nonrecoverable.

UTILIZATION OF ASPIRATED WINDOW EFFLUENT DURING SOLAR ACCEPTANCE MODE OPERATION

A number of applications of the aspirated window effluent is anticipated. It is generally recognized that buildings with superb thermal barriers have to make provision for adequate air for ventilation. It appears reasonable, in light of the considerations discussed herein, that air for winter ventilation be brought into the conditioned space through a solar irradiated multipane window system--thereby preheating the air, suppressing heat losses to the exterior and recovering the net solar absorbtivity heating of the window system. Where the net absorbtivity of the window system is small, compared to a typical active collector, small flow rates can be employed to achieve the desired effects.

In some winter time cases, it may be most efficient to flush the insolated aspirating window system at a mass flow rate which is substantially larger than that prescribed by a need for ventilating air. In such cases, we may want to consider devices which can transfer the enthalpy of very warm ventilating air to another form. Thermal storage systems can achieve some of this. Also, heat pumps and other HVAC devices can recover substantial fractions of the enthalpy available in effluents of aspirated, solar-irradiated windows.

THE COUNTERFLOW HEAT EXCHANGER

The aspirated window system currently under study is a form of counterflow heat exchanger. The technology is well established and the enormous suppression of reverse heat transfer at the cold boundary is a well known effect for counterflow heat exchangers. The multipane aspirated window system is a folded, regeneratively cooled/heated version of a counterflow heat exchanger.

CONCLUSIONS

An aspirated solar collector (hybrid active-direct gain) window system may be used advantageously during all seasons. Although problems of flow stability and optimum heat transfer characteristics must be addressed, it appears that design methods and constraints are available for easy achievement of the full range of objectives.

For the three-pane hybrid window system, the efficiency of the hybrid window is higher than that of its passive counterpart, inasmuch as the cold boundary heat losses are suppressed <u>and</u> the enthalpy associated with the window's net solar absorbtivity is largely recovered.

For the three pane hybrid window system, the efficiency of the hybrid window is greater than that of its active counterpart, for reasons similar to the aforementioned. It appears that the hybrid (aspirated, solar irradiated) window offers performance advantages not provided as fully by either its passive or active counterpart.

When used in a nighttime, closed, apssive mode, the three pane window system has an R-value which is greater than 15 $ft^2 \cdot hr \cdot {}^oF/Btu$. It is expected that an aspirated nighttime operating mode can further improve on this non-solar-acceptance mode's performance.

The window system under study is useful for beam daylighting purposes.

During cooling season operation, the three pane window system can be used in either a passive or active mode to provide shading and a very high effective R-value. In a passive mode (closed) it has an R value of about $2.64 m^2 \cdot {}^oC/W$ (or 15 $ft^2 \cdot hr \cdot {}^oF/Btu$). In an active mode (but with blinds "closed" or in a "shading" position), the counter current flow is expected to reduce the heat gain of the conditioned space even further.

Finally, note that the general approach discussed here is applicable to the suppression of unwanted heat losses in non-transparent elements of a building's thermal barrier. Multi-pass, regenerative air flow through low emissivity, properly cellularized wall sections should provide DYNAMIC INSULATION of very high R-value. The mode, performance, and utility of various aspirating transparent and non-transparent thermal barrier elements are under current study.

REFERENCES

1. ASHRAE: "Handbook of Fundamentals." 1977.

2. Hollands, K. G. T., "Natural Convection in Horizontal Thin-Walled Honeycomb Panels." J. Heat Transfer, 439 (November 1973).

3. Berman, S. M. and Silverstein, S. D., "Efficient Use of Energy-III. Energy Conservation and Window Systems. AIP Conference Proceedings No. 25, 1975.

4. Berlad, A. L., Tutu, N., Yeh, Y. J. and Jaung, R., "Design and Performance of Low Heat Loss Window Systems." Paper presented at May 28 - June 1, 1978 International Solar Energy Congress (Atlanta, Georgia). In press.

5. Puri, V. M., "Transmittance of Diffuse Solar Radiation Through a Series of Parallel Regions," Solar Energy 22, No. 2, 183 (1979).

6. Kreider, J. F. and Kreith, F., "Solar Heating and Cooling." Pub.: Hemisphere Publishing Corp. (1975).

7. Berlad, A. L., Salzano, F. J., and Batey, J., "On Enthalpy Management in Small Buildings," Energy 1, 429 (1976).

8. Caouris, Y., et al, "A Novel Solar Collector." Solar Energy 21, No. 2, 157 (1979).

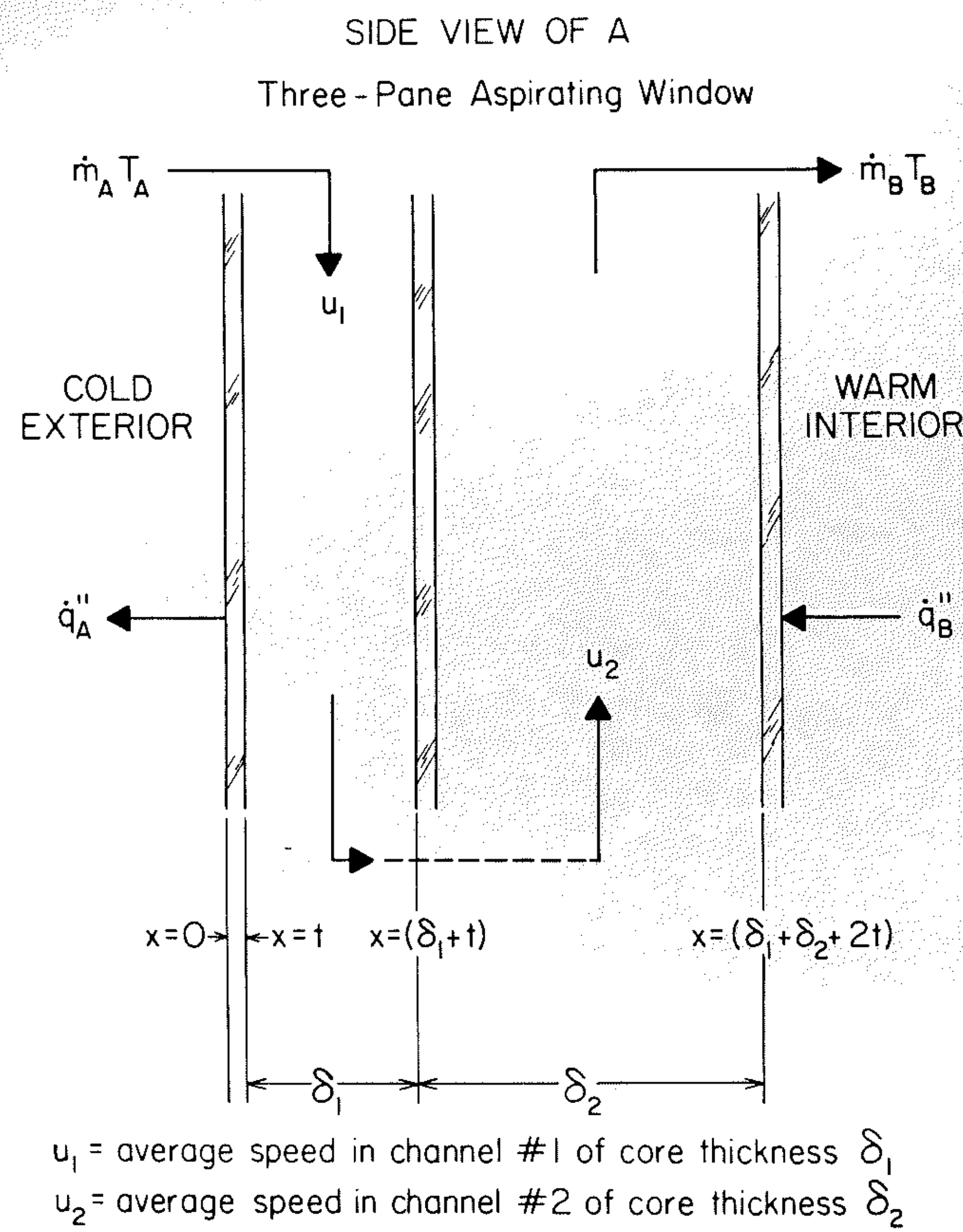
9. Berlad, A. L., Yeh, Y. J., Jaung, R. and Tutu, N., "Energy Transport Control in Window Systems." Proc. Second National Passive Solar Energy Conference. P. 326 (1978).

10. Rao, T. L. S. and Morris, W. D., "Superimposed Laminar Forced and Free Convection Between Vertical Parallel Plates---." Paper No. 40. Thermodynamics and Fluid Mechanics Convention. Bristol, England 27-29 March 1968. Pub.: The Institute of Mechanical Engineers.

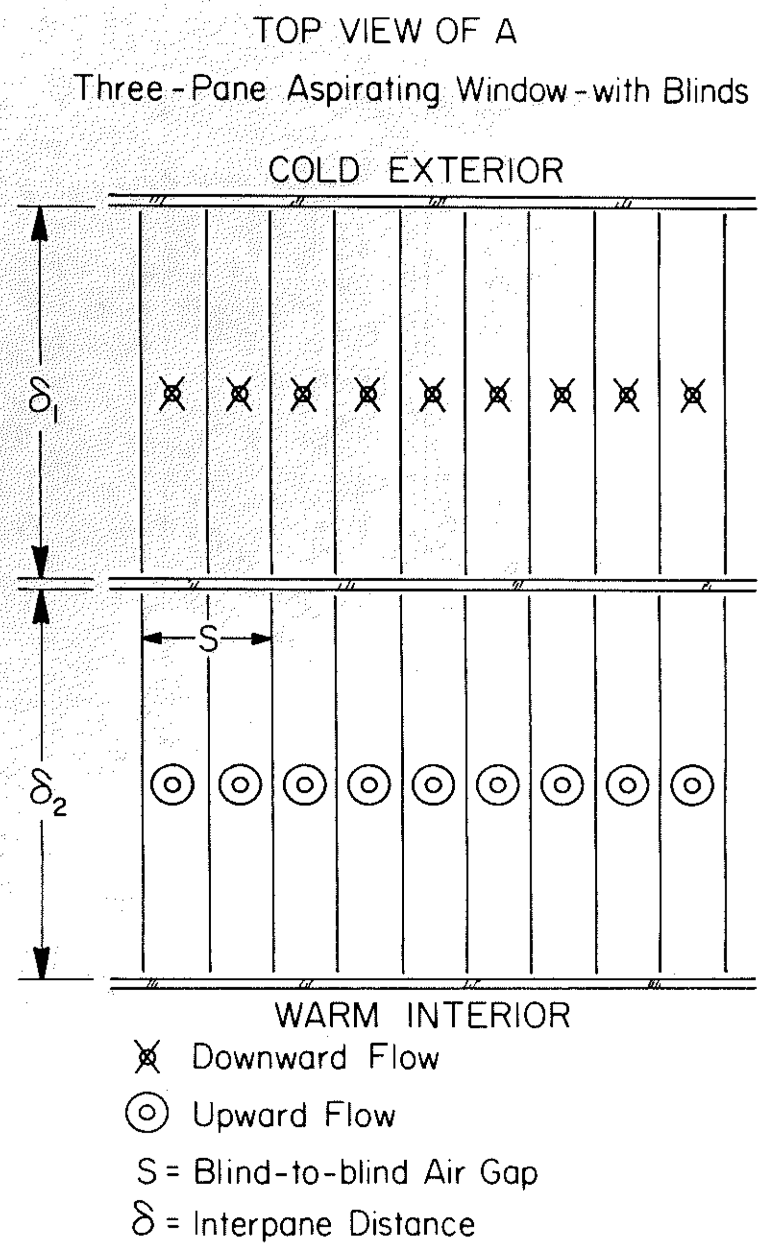
11. Berlad, A. L., Salzano, F. J., and Batey, J., "Energy Transport Control in Window Systems." Brookhaven National Laboratory Report BNL 50586 (September 15, 1976).

12. Sherwin, K. and Wallis, J. D., "A Study of Laminar Convection for Flow Down Vertical Annuli." Thermodynamics and Fluid Mechanics Convention. Proc. Inst. Mech. Engrs. 1967-68, 182 (Part 3H), 330.

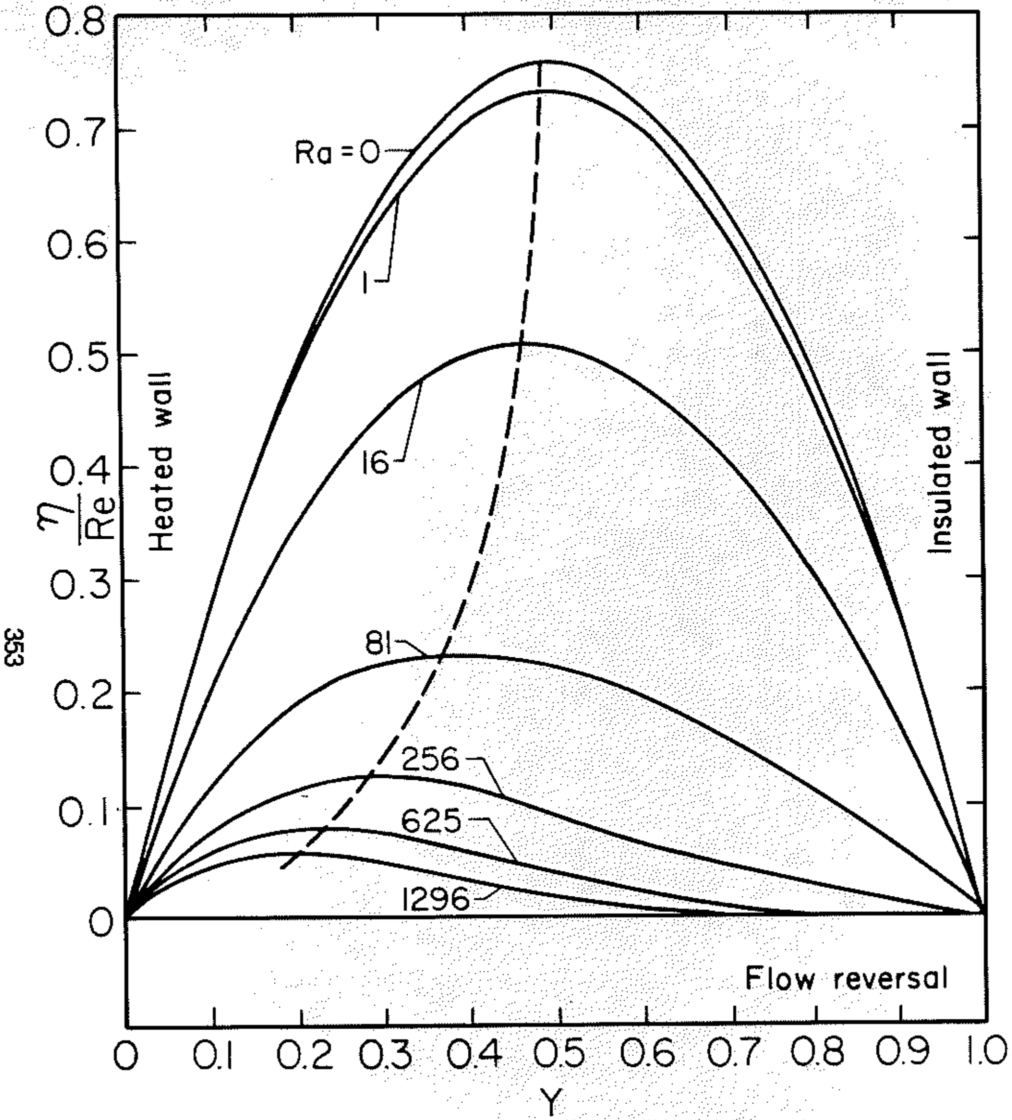
13. Sherwin, K. and Wallis, J. D., "Combined Natural and Forced Laminar Convection for Upflow Through Heated Vertical Annuli." Proc. Inst. Mech. Engrs. Paper C112/71 (May 10, 1971).



(1) Side View of a Three-Pane Aspirating Window (Schematic)

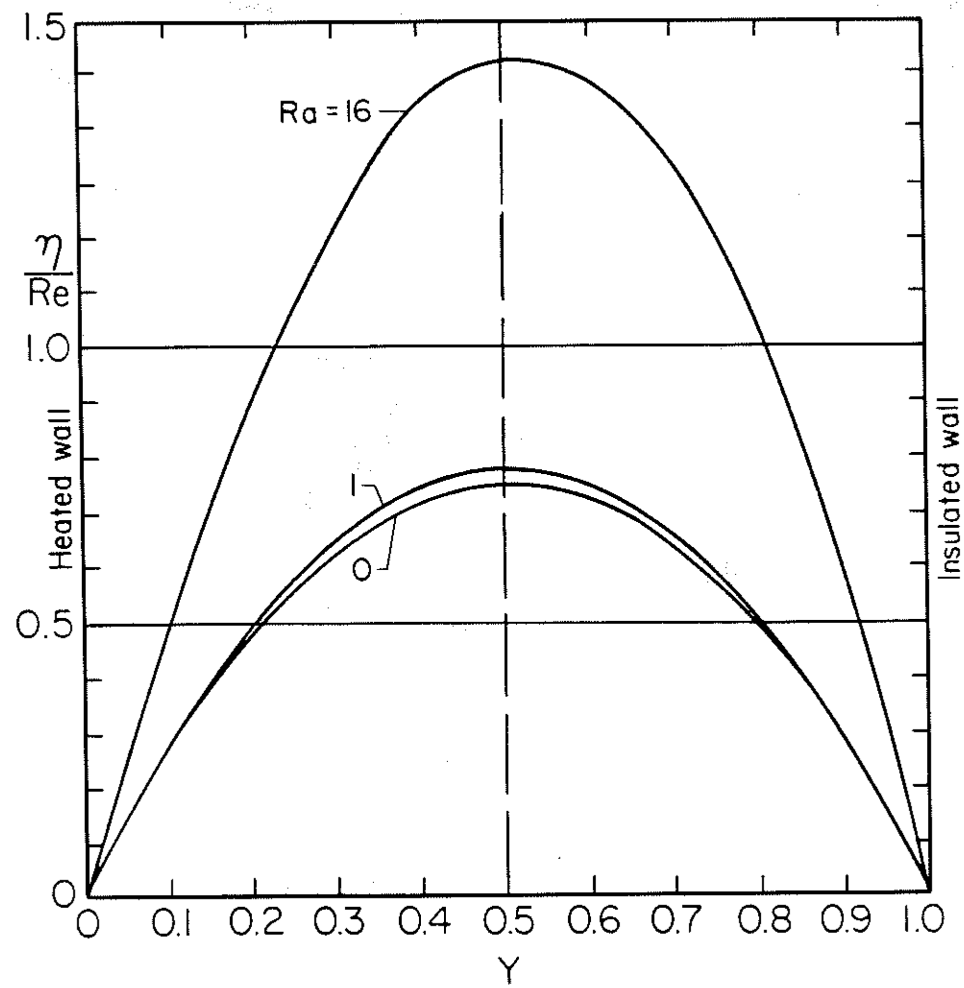


(2) Top View of a Three-Pane Aspirating Window -- with Blinds (Schematic)



Velocity profiles for heated upward flow.

(3) Velocity Profiles for Heated Upward Flow (Reference 10)



Velocity profiles for cooled upward flow.

(4) Velocity Profiles for Cooled Upward Flow (Reference 10)