# EFFECTIVE U-VALUES AND SHADING COEFFICIENTS OF PREHEAT/SUPPLY AIR GLAZING SYSTEMS

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## ABSTRACT

Research is documented which makes use of a computer program called VISION. This computer program was developed specifically to provide a detailed analysis of heat transfer occuring in glazing systems. VISION was modified to perform an analysis of the energy flows in supply air windows. A model used to quantify heat transfer in the supply air flow is described. Ventilation air is brought in through supply air windows and the energy recovered by the preheat of the air flow is credited to the thermal performance of the window itself. Thus, the net energy flow between the conditioned space and the window was used to calculate an effective U-value and shading coefficient. The use of these "effective" window performance parameters permits the subsequent quantification of energy flows to or from the supply air glazing system without the necessity of modelling the detailed mechanisms of energy transport within the glazing system itself. A variety of glazing system designs are simulated. Indoor glazing temperature is reported for each system. In all cases the presence of preheat ventilation improved the effective shading coefficient moderately and increased the effective thermal resistance appreciably.

## INTRODUCTION

Substantial energy conservation benefits are attainable through the use of "supply air windows". In order to reduce the space heating load the supply air required for ventilation passes into the building by way of a flow path provided within the glazing system instead of through leakage sites or openings located elsewhere in the building envelope. This glazing system arrangement is shown conceptually in Figure 1. Figure 1 also shows the numbering system that is applied to the indoor, outdoor, supply air and individual glazing temperature nodes. As the air passes between the glazings it is preheated by drawing on absorbed solar gains and/or thermal losses from the building interior. The need to restrict supply air flow solely to the window passages indicates that supply air windows should perform well when installed in a very airtight building envelope and used in conjunction with an exhaust air device that holds the building at a slightly negative pressure.

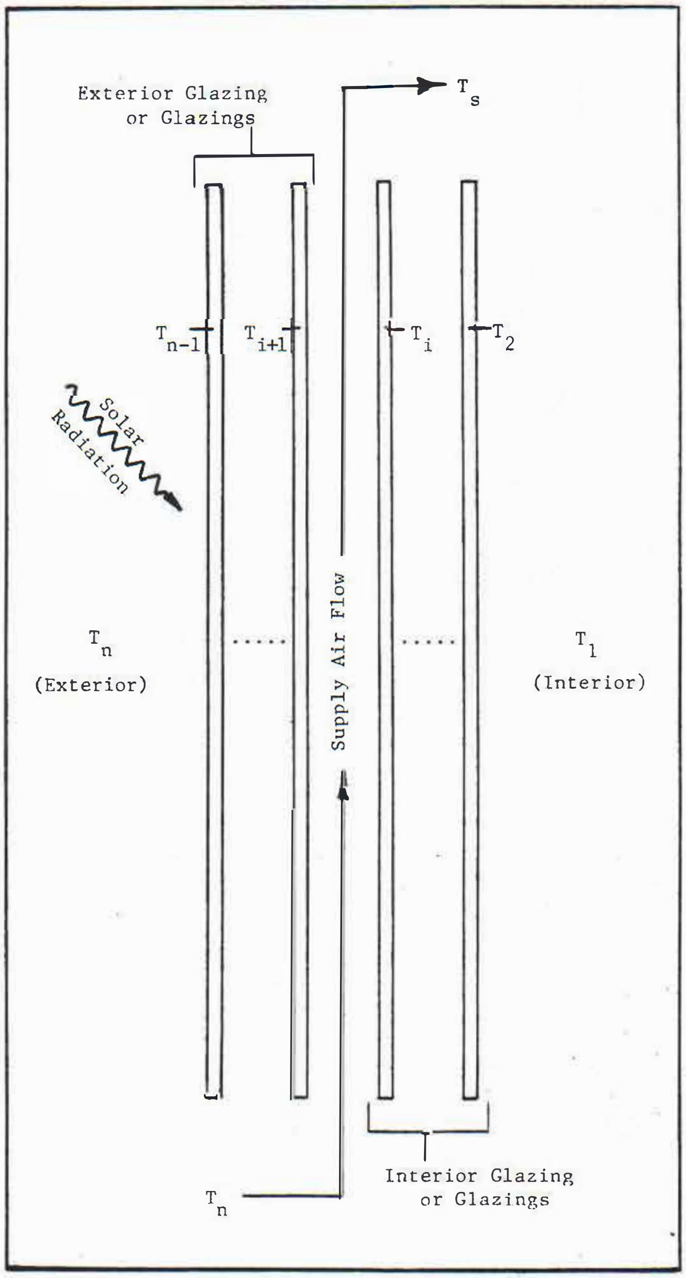



Figure 1: Preheat/Supply Air Flow Concept

Results of the relatively modest amount of research that has been performed on supply air windows are encouraging. Korkala, etal [1] examined some practical aspects of several double glazed configurations showing that useful amounts of supply air could be taken in without serious loss of thermal comfort. Barakat has noted [2] a decrease in required space heating energy of about 25% when one unit of the NRC Passive Solar Facility [3] (located in Ottawa) was fitted with triple glazed supply air windows and compared to a similar unit fitted with conventional double glazed windows. A decrease in required energy was also noted when triple glazed supply air windows were compared to conventional triple glazed windows.

The VISION computer program [4] has been modified in order to simulate the performance of supply air glazing systems. VISION was developed specifically to provide reliable U-value and shading coefficient estimates for innovative glazing systems. Heat transfer within the glazing system is quantified using a detailed one dimensional (1-D) analysis. The capabilities of this analysis have been extended to include the treatment of supply air flow between glazings without resorting to a major rewrite of the VISION source code. Instead, the existing program has been modified to only a limited degree and is tricked to model the internal air flow. The conduction/convection heat transfer rates from the walls adjacent the forced air flow are determined using a two dimensional (2-D) analytical solution [5] of basic equations describing the elemental energy balance in the fluid flow. The two solutions that are applied - one dealing with heat transfer between glazings and the other with the heat transfer to the forced flow of supply air - are well suited to be applied simultaneously since both are based on the assumption that each glazing is isothermal.

The results of this analysis serve not only to support the intuitive and qualitative understanding of preheat/supply air glazing systems. In addition they provide quantitative feedback regarding the merits of various design options, their energy conservation potential and the principles governing their operation. For instance, it is recognized that the flow of supply air between the glazings will lower the temperature of the indoor glazing. Indoor glazing temperature is reported for each system simulated in order to determine the change in allowable indoor humidity.

Glazing system designs range from a simple double glazed system to more complex configurations involving the use of two, three or four glazings, low emissivity (low E) coatings and argon fill gas.

## THE SUPPLY AIR FLOW MODEL

The following paragraphs present an overview of the technique used to model the heat transfer between the glazing system and the supply air flow. This presentation is not complete in every detail. The remaining information can be found in the references provided. The nomenclature needed to understand this analysis is shown in Figure 2.

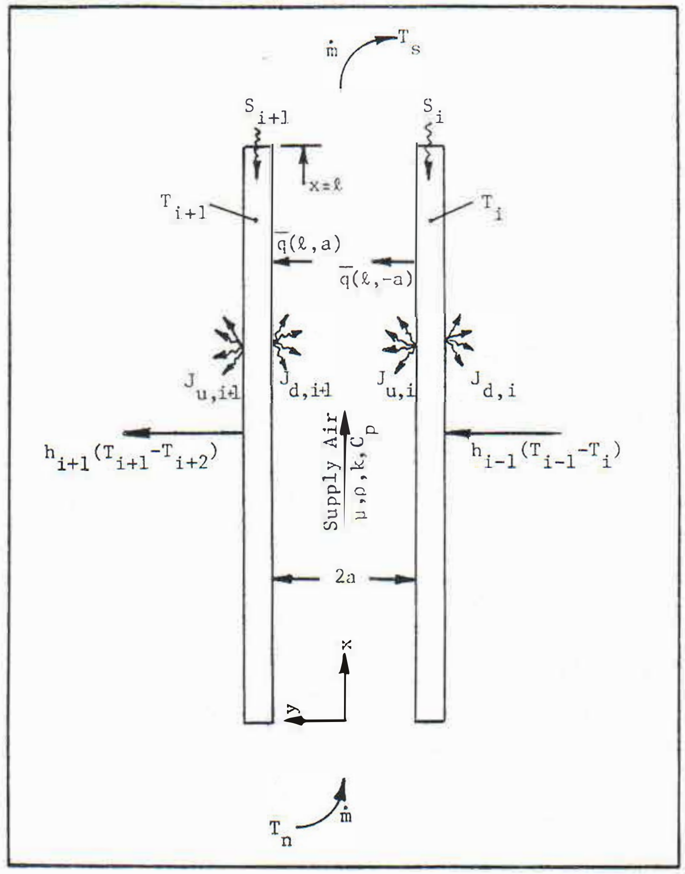



Figure 2: The Supply Air Flow Model

It can be shown that the Reynolds number based on hydraulic diameter and average air speed, $Re_D$, of the supply air flow is given by:

$$Re_D = 2\dot{m}\ell/\mu \qquad (1)$$

where $\dot{m}$ is the mass flow rate per unit aperture area, $\mu$ the dynamic viscosity of the air and the length of the flow path is $\ell$. $\ell$ is equal to the height of the window. Note that the hydraulic diameter, D, is equal to four times the half width of the flow gap.

$$D = 4a \qquad (2)$$

The value of $\dot{m}$ can be calculated using equation 3.

$$\dot{m} = \rho H(A_f/A_a)ACR \qquad (3)$$

where $\rho$ is the air density, H is ceiling height, ACR is the air change rate and $A_f/A_a$ is the ratio of floor area to aperture area. Based on the following assumed values,

H = 2.44 m

ACR = 0.5 air changes per hour

and $A_f/A_a = 10$

the value of $\dot{m}$ was taken to be 15.6 Kg $m^{-2}$ $hr^{-1}$ for all simulations carried out. Further assuming that $\ell$=1m the Reynolds number was estimated to be $Re_D$=525.

The Reynolds number result shown above indicates that the supply air flow can safely be assumed to be laminar in nature. Referring to equation 1, it can be seen that the height of the window can approach 4m before the critical Reynolds number marking the onset of turbulence (approx. 2000) is approached. The supply air flow in all simulations is treated as laminar, steady and fully developed.

An energy balance applied to an elemental control volume in the supply air flow, while neglecting conduction in the flow direction, yields equation 4:

$$u(\partial T/\partial x) = \alpha(\partial^2 T/\partial y^2) \quad (4)$$

where $\alpha$ is the thermal diffusivity of the air and u is the velocity component in the x direction. Solutions to equation 4 can be found in references 5 through 10 among others. The particular solution used in this analysis is found in reference 5 where Cess and Shaffer express the 2-D temperature solution in terms of Stieltjes integrals. Application of the Fourier-Biot law to the temperature field yields an expression for the local heat flux in the y direction.

$$q(x,y) = (-k/a)[(1 - 2\theta'(x,y))(T_{i+1}-T_n) + (-1 + 2\theta'(x,-y))(T_i-T_n)]/2 \quad (5)$$

Once the flow space half width, a, and the Peclet number are fixed the function $\theta'(x,y)$ is a function of x and y only. The Peclet number, Pe, is given by:

$$Pe = Re_D\ Pr \quad (6)$$

where Pr is the Prandtl number of the air flow. An expression for $\theta(x,y)$ is given in reference 5.

The average heat flux to the supply air at the adjacent glazings can be found by setting y=a or y=-a in equation 5 and integrating with respect to x from x=0 to x=$\ell$.

$$\bar{q}(\ell,a) = (1/\ell)\int_0^\ell q(x,a)\ dx \quad (7)$$

$$\bar{q}(\ell,-a) = (1/\ell)\int_0^\ell q(x,-a)\ dx \quad (8)$$

These average heat transfer rates, $\bar{q}(\ell,a)$ and $\bar{q}(\ell,-a)$ are shown in Figure 2. The net heat flux from the glazings to the supply air is given by:

$$q_s = \bar{q}(\ell,-a) - \bar{q}(\ell,a) \quad (9)$$

and can be used to calculate the temperature of the supply air as it leaves the glazing system, $T_s$.

$$T_s = T_n + q_s/(\dot{m}C_p) \quad (10)$$

where $C_p$ is the specific heat of the supply air.

## INCORPORATION OF THE SUPPLY AIR MODEL

The VISION computer program quantifies the various energy flows within a glazing system by simultaneously applying an energy balance to each individual glazing. Reference 4 can be used as a complete source of detailed information. This energy balance applied at the $i^{th}$ glazing is given by equation 11.

$$h_{i-1}(T_{i-1} - T_i) + J_{u,i-1} - J_{d,i} + S_i = h_i(T_i - T_{i+1}) + J_{u,i} - J_{d,i+1} \quad (11)$$

The heat transfer coefficients, $h_{i-1}$ and $h_i$, are used to quantify convective heat transfer from glazing i-1 to glazing i and from glazing i to glazing i+1, respectively. The quantities $J_u$ and $J_d$ represent radiosities that account for various upward and downward (in this case outdoor and indoor) bound fluxes of thermal radiation. Solar radiation which is absorbed at the $i^{th}$ glazing and appears as an energy source is equal to $S_i$.

Referring to the $i^{th}$ glazing shown in Figure 2 it can be seen that equation 11 cannot be directly applied. The heat transfer coefficient $h_i$ has no apparent meaning in the supply air gap. Instead, the VISION computer code is tricked using a two step procedure. First, the coefficient $h_i$ at the air flow gap is set equal to zero. This eliminates what VISION sees as convective heat transfer across the gap. Second, VISION is supplied with a modified source term, $S_i'$, in the place of $S_i$. $S_i'$ represents the energy source due to absorbed solar radiation minus the energy lost to the supply air flow.

$$S_i' = S_i - \bar{q}(\ell,-a) \quad (12)$$

Substitution into equation 11 yields a more meaningful energy balance.

$$h_{i-1}(T_{i-1} - T_i) + J_{u,i-1} - J_{d,i} + S_i' = J_{u,i} - J_{d,i+1} \quad (13)$$

Applying the same procedure at glazing i+1 gives:

$$S'_{i+1} = S_{i+1} + \bar{q}(\ell,a) \qquad (14)$$

and

$$J_{u,i} - J_{d,i+1} + S'_{i+1} = h_{i+1}(T_{i+1} - T_{i+2}) + J_{u,i+1} - J_{d,i+2} \qquad (15)$$

VISION incorporates an iterative procedure where glazing temperatures are determined as a function of the various heat transfer coefficients within the glazing system/-environment array. At each iteration the heat transfer coefficients are updated and iteration continues until the temperature solution converges. In the supply air solution the heat flux to the supply air was also updated at each iteration. When convergence was reached a full solution including all glazing temperatures, heat transfer rates and supply air temperatures had been found.

## CALCULATION OF EFFECTIVE U-VALUE

The U-value is calculated using an indoor temperature of $T_1$=21 C, an outdoor temperature of $T_n$ = -18 C, a fraction cloud cover of 0.5 and zero solar radiation. See reference 4 for more detail. VISION performs this calculation using the total heat flux from the conditioned space to the interior glazing. An effective U-value, $U_e$ , can be calculated by crediting the window with the energy gained by the supply air flow, $q_s$.

$$U_e = [h_1(T_1 - T_2) + J_{u,1} - J_{d,2} - q_s]/(T_1 - T_n) \qquad (16)$$

In the absense of solar radiation the heat flux from the interior to the inside glazing is greater than the heat flux from the outside glazing to the exterior environment by the amount of energy transferred to the supply air, $q_s$. Therefore, a simpler expression for the effective U-value is:

$$U_e = [h_{n-1}(T_{n-1} - T_n) + J_{u,n-1} - J_{d,n}]/(T_1-T_n) \qquad (17)$$

## CALCULATION OF EFFECTIVE SHADING COEFFICIENT

The shading coefficient is calculated in the absence of indoor/outdoor temperature difference ($T_1$=$T_n$=19 C), 741 W $m^{-2}$ of incident solar radiation and zero cloud cover. Reference 4 provides detailed information. The effective shading coefficient , $SC_e$ , is found when the window is credited with the supply air energy gain, $q_s$, in addition to the customary quantities of absorbed/retransmitted and directly transmitted solar gain. The total energy gain is divided by the energy gain of a conventional single glazed window subjected to the same conditions , $q_{ref}$.

$$SC_e = [h_1(T_2 - T_1) + S_1 + q_s]/q_{ref} \qquad (q_{ref} = 612.3 \text{ W m}^{-2}) \qquad (18)$$

## OPTICAL PROPERTIES

All of the glazing systems simulated consisted of conventional glass with or without one of two types of low E coating. Input data used to characterize the solar properties of glass were index of refraction (n=1.52) and extinction coefficient (K=0.024 $mm^{-1}$). All glazings were taken to be 3.175 mm thick. The glass/low E glazing element was modelled as having 60% normal solar transmissivity, and normal reflectivities of 25% and 22% with respect to solar radiation incident from the coating or substrate sides, respectively.

The hemispheric/hemispheric long wave ( $\lambda$ >3μm) properties were specified such that all glazings were opaque. The emissivities of the low E coating used in sealed spaces and of plain glass were 0.09 and 0.84, respectively. In cases where a low E coating was used in an air flow gap the emissivity was set at 0.35 in order to model the more durable coating that would be required.

## SIMULATION RESULTS

Computer simulations were carried out for eleven different glazing systems that incorporate a variety of low E coating(s), air flow locations and fill gas options. All pane spacings including the supply air flow gap were set at 15 mm. Each glazing system was simulated with and without supply air flow. Thus, four primary results consisting of two U-values and two shading coefficients were calculated for each system. These simulation results plus a variety of intermediate calculation results are presented in Table 1.

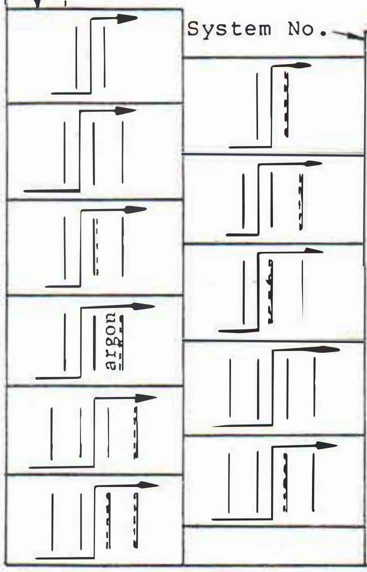
Examining the U-value results shown in the left hand portion of Table 1 a number of observations can be made. In all of the glazing systems simulated the presence of supply air flow reduced the U-value. Although the amount of reduction in U-value might vary widely from one system to another, it is noteworthy that this reduction was always appreciable. The smallest U-value reduction was 31%.

It is also remarkable that the U-value reduction can be greater for systems that are more intricate and that have relatively low U-values without supply air flow. Most of the two and three glazing systems exhibit a 30 to 40% U-value reduction but all of the four glazing systems provide a reduction of more than 50% when supply air is used. This sizeable reduction of an already low U-value results in exceptionally low effective U-values. For instance, system eleven shows a 58% reduction in U-value giving an effective U-

**TABLE 1: PREHEAT/SUPPLY AIR SIMULATION RESULTS**

Subscript "e" indicates presence of supply air

Marks low E coating




| System No. | U-VALUE | | | | | SHADING COEFFICIENT | | | |
|---|---|---|---|---|---|---|---|---|---|
| | U $W/m^2C$ | $T_2$ C | $T_{2,e}$ C | $T_s$ C | $U_e$ $W/m^2C$ | $S_1$ $W/m^2$ | SC | $q_s$ $W/m^2$ | $SC_e$ |
| 1 | 2.88 | 6.2 | 4.3 | -6.7 | 1.94 | 501.2 | 0.87 | 10.4 | 0.88 |
| 2 | 2.35 | 9.1 | 7.3 | -5.7 | 1.30 | 358.6 | 0.71 | 21.0 | 0.72 |
| 3 | 1.84 | 11.8 | 10.9 | -11.0 | 1.22 | 425.4 | 0.78 | 19.8 | 0.80 |
| 4 | 1.32 | 14.5 | 13.9 | -13.1 | 0.88 | 307.3 | 0.65 | 26.5 | 0.68 |
| 5 | 1.32 | 14.5 | 13.9 | -13.1 | 0.88 | 306.9 | 0.60 | 41.8 | 0.65 |
| 6 | 1.59 | 13.1 | 12.1 | -9.9 | 0.87 | 306.9 | 0.63 | 36.7 | 0.67 |
| 7 | 1.12 | 15.5 | 14.9 | -13.8 | 0.76 | 307.3 | 0.65 | 26.4 | 0.68 |
| 8 | 1.34 | 14.4 | 11.7 | -7.5 | 0.67 | 362.5 | 0.71 | 40.6 | 0.74 |
| 9 | 1.01 | 16.1 | 14.4 | -10.5 | 0.49 | 263.7 | 0.59 | 53.3 | 0.65 |
| 10 | 1.19 | 15.2 | 12.5 | -7.4 | 0.51 | 263.6 | 0.59 | 58.1 | 0.63 |
| 11 | 0.90 | 16.6 | 14.9 | -10.3 | 0.38 | 194.8 | 0.49 | 77.2 | 0.57 |

value of 0.38 W $m^{-2}$ $C^{-1}$. This is equivalent to a thermal resistance of RSI 2.6 or R 14.9.

The results of the U-value calculations also highlight a relationship between the location of the supply air flow (or the location of thermal resistance) and supply air temperature, $T_s$. As more thermal resistance is added between the supply air flow and the conditioned space the temperature of the supply air flow drops. Compare system one and system three. The addition of one glazing on the interior decreases effective U-value by 37% but at the same time the supply air temperature drops from -6.7 C to -11.0 C. A similar comparison can be made between systems three and four where the only change is the addition of one low E coating. On the other hand the addition of thermal resistance between the supply air gap and the exterior environment not only decreases the effective U-value but an increase in supply air temperature is produced at the same time. This effect can be seen by comparing systems three and eight, four and nine or six and ten.

The inside glazing temperature also varies according to the presence of supply air flow and as a function of the placement of thermal resistance. The presence of supply air always reduces the temperature of the inside glazing. If thermal resistance is added anywhere in the glazing system the temperature of the inner glazing rises and approaches the temperature of the conditioned space. Compare systems three and four, three and six as well as three and eight. However, it is worth noting that only in the case of system one itself was the inside glazing temperature - with supply air present - lower than the inside glazing temperature of a conventional double glazed system (system one) operated without supply air flow. The inside glazing temperature of system three with supply air flow was 10.9 C. This surface temperature corresponds to an allowable relative humidity level in excess of 50%.

The use of a low E coating in the supply air flow gap illustrates an interesting phenomenon. Compare systems five and six. These two configurations provide essentially the same effective U-value but system six delivers supply air at -9.9 C rather than -13.1 C. The same effect can be seen by comparing systems nine and ten. A low E coating placed in the air flow gap suppresses overall heat transfer by reducing radiative exchange across this gap but does not act to reduce the energy transferred directly from the interior to the supply air. In contrast, a low E coating placed in the interior side sealed space does reduce energy flow from the interior to the supply air causing the supply air to enter the room at a lower temperature. As a result of this effect, a low E coating placed in the flow air gap, rather than in the interior side sealed gap, appeared to be of greater benefit. Not only were the resulting supply air temperatures higher but the effective U-values were comparable in spite of the higher emissivity of the durable low E coating used in the flow air gap.

The shading coefficient calculation results shown on the right hand side of Table 1. also show a number of interesting trends. In all systems simulated the presence of supply air flow increased the shading coefficient. Most of these increases are marginal - in the range of from 1 to 5%. Similar to the change in U-value the increase in shading coefficient was greater, as a general trend, for more intricate glazing systems. For example, the shading coefficient of system eleven which has four panes and two low E coatings increased by 16% when supply air was introduced. On the other hand, the more intricate glazing systems have lower shading coefficients and effective shading coefficients as a general rule.

The effective shading coefficient appears to be relatively insensitive to the location of low E coatings that are placed between the supply air flow and the interior. Compare systems four to system five or six. In system four the solar radiation that is absorbed at the low E coating can readily transfer to the conditioned space directly. In systems five and six the solar radiation absorbed at the coating more readily transfers to the supply air and is again supplied to the interior. In the latter case the supply air is given more preheat energy.

## CONCLUDING REMARKS

A calculation method has been presented which makes possible the analysis of a preheat/supply air flow passage within the framework of the VISION computer program. Results are consistent with intuition regarding the mechanisms governing operation of this type of window. Reliable generalizations or "rules of thumb" are difficult to make when dealing with the design of supply air windows. The number of design options is extremely large. Where particular design options are considered a detailed simulation of each system is recommended.

It is noted that the introduction of supply air flow consistently decreased the U-value and increased the shading coefficient of the various glazing systems simulated. These changes were generally larger for more intricate glazing designs. The effective U-values of four glazing systems can be exceptionally small without seriously sacrificing solar gains.

The use of multiple panes and low E coatings can be used to tailor effective U-value and effective shading coefficient in much the same way as is possible with conventional glazing systems. Similar trade-offs exist. In addition, there exists a trade-off between increasing the temperature of the supply air flow and lowering the temperature of the interior glazing. Results from the simulations carried out indicate that interior glazing temperatures are not low enough to aggravate water condensation problems in all but the very simple double glazed system. In light of this finding, it is expected that glazing system design can be more directly determined by the possibility of maximizing the temperature of the supply air. In order to accomplish this goal the use of a durable low E coating in the air flow gap looks promising and warrants further attention.

Effective U-values and effective shading coefficients can be used directly in the place of U-values and shading coefficients as input to building energy analysis programs. However, caution must be exercised because these results are based on a specific rate of ventilation air flow inward (per unit aperture area) at the building envelope. This same inflow rate of unheated air must be included in the building energy analysis. The superior performance of the supply air/preheat window relies on the fact that this ventilation air would be required regardless of its infiltration path.

The work presented in this study raises many questions. It is intended that future work will include prototype testing, the simulation of multiple pass supply air flow passages as well as the sensitivity analysis of performance results with respect to air flow rate and the length and thickness of the air flow gap.

## REFERENCES


[1] Korkala, T., Saarnio, P., Siitonen, V., "Air Intake Arrangements of the Supply Air Window from the View of Comfort and Ventilation Efficiency", Proceedings of the Windows in Buildings Conference, Sweden, June, 1984

[2] Barakat, S.A., Personal communication, December, 1985

[3] Barakat, S.A., "NRCC Passive Solar Test Facility Description and Data Reduction", DBR/NRC Technical note BRN #214, May, 1984.

[4] Ferguson, J.E., Wright, J.L. "VISION: A Computer Program to Evaluate the Thermal Performance of Super Windows", Solar Energy Program, NRC report no. Passive-10.June, 1984.

[5] Cess, R.D., Shaffer, E.C., "Summary of Laminar Heat Transfer Between Parallel Plates With Unsymmetrical Wall Temperatures", Journal of the Aero/Space Sciences, August, 1959, page 538.

[6] Lundberg, R.E., Reynolds, W.C., Kayes, W.M., "Heat Transfer with Laminar Flow in Concentric Annuli with Constant and Variable Wall Temperature with Heat Flux", NASA TN D-1972, Washington, August, 1963.

[7] Yih, C.S., Cermack, J.E., "Laminar Heat Convection in Pipes and Ducts", Civel Engineering Department, Colorado Agricultural and Mechanical College, Fort Collins, Colorado, September, 1951, ONR Contract No. N90nr-82401, NR 063-071/1-19-49.

[8] Prins, J.A., Mulder, J., Schenk, J., "Heat Transfer in Laminary Flow Between Parallel Plates", Applied Scientific Research, Section A Vol 2, pp. 431-438, 1949-51.

[9] Schenk, J., Beckers, H.L., "Heat Transfer in Laminar Flow Between Parallel Plates", Applied Scientific Research, Section A, Vol 4, pp. 405-413, 1953-54.

[10] Sellars, J.R., Tribus, M., Klein, J.S., "Heat Transfer in Laminar Flow in a Round Tube or Flat Conduit - The Graetz Problem Extended, Trans. ASME, Vol. 78, pp. 441-448, 1956.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