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Final Report:

**Development of a Procedure for U-Factor Rating
of Domed Skylights**

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1. EXECUTIVE SUMMARY

This research was undertaken under the grant with National Fenestration Rating Council in an effort to develop heat transfer correlations for domed skylights, leading to the development of simulation method for U-factors and SHGC of domed skylights and other products that incorporate similar geometries.

Literature review of the published numerical and experimental studies on convection heat transfer in curvilinear spaces was done to present current state-of-the-art and to identify potentially useful body of work for this study. Most of the identified work had limited usability and confirmed the need for the development of new set of heat transfer correlations that would be used in NFRC rating process.

Survey of the market and current practices in North America identified three distinct types of domed skylight glazing systems so they were categorized in Type-A, Type-B, and Type-C. Type-A and Type-B are double glazing layer configurations, while Type-C were triple and quadruple configurations. It was concluded that Type-C glazing systems can be constructed by combining Type-A and/or Type-B glazing cavities, so the detailed heat transfer analysis was done for Type-A and Type-B only.

Before numerical modeling was done, rules were developed for generating domed skylight glazing cavities by using geometrical primitives, which led to the identification of basic geometric parameters, radius of curvature, glazing base, maximum gap width and combination of those (e.g., aspect ratio, etc.). Formulas based on geometry analysis were developed to construct 3-D numerical models.

Preliminary numerical analysis indicated that it will be necessary to develop 3-D numerical models, as 2-D models were not adequate in capturing all of the flow and heat transfer details in non-uniform domed skylight glazing cavities.

3-D numerical modeling, utilizing laminar viscous convection heat transfer model and 3-D view-factor based radiation model were developed for Type-A and Type-B domed skylight glazing cavities and detailed heat transfer results, based on runs with range of boundary conditions and geometry parameters were presented and used in the development of generalized heat transfer correlations.

Experimental validation of numerical results were carried out for both Type-A and Type-B domed skylight glazing systems using innovative experimental technique for obtaining local heat transfer fluxes and temperatures. Experimental results agreed very well with the numerical models, giving confidence to the full numerical study used for the development of convective heat transfer correlations.

2. INTRODUCTION

2.1 Background

Domed skylights represent broad range of products in which transparent portion of the product is comprised of curvilinear geometry, forming uneven glazing cavities. These

products are typically manufactured from polymer materials which are easier to form into the curvilinear shapes. These products are very different from the standard fenestration products incorporating plane glazing, separated by a uniform gap. The reason for their curvilinear geometry is to maximize their visible transmittance at of-normal angles. This is due to their primary purpose, which is to provide daylighting in spaces. Often, these products are arranged in double or triple configurations (rarely quadruple configurations), where each dome roughly corresponds to the section of sphere. The space between them often resembles geometry that would be obtained if two spheres with the same or different radii are intersected. When the sphere has same radii, then space with uniform distance is obtained, while in the former case variable gap width space is obtained. Also, some domed skylight glazing products are formed by using one or more flat glazing in combination with one or more curvilinear glazing.

Currently NFRC, as well as other relevant domestic and international standards (NFRC 100, ISO 15099, ISO 10077, etc.) do not provide any heat transfer correlations for these non-uniform curvilinear geometries, so the only way to rate such products at NFRC is to measure their thermal and solar-optical performance. These systems can be oriented horizontally, or at an angle. NFRC rates skylights at an angle of 20°, but validates simulations at vertical orientation. For these reasons all simulations were carried at vertical orientations and 20° tilt from horizontal. Experimental validation was done for vertical glazing only.

2.2 Objectives

The main objective of this research project is to develop set of convection heat transfer correlations for equidistant or variable spacing domed skylight glazing cavities found in typical North American domed skylights. These correlations are intended to be in a form that is easily incorporated into the NFRC rating tools WINDOW and THERM.

3. LITERATURE REVIEW

There are currently very limited numerical or experimental studies of the convection heat transfer in curvilinear spaces with varying cavity width between glazing layers. These are the geometries and configurations that are typical of domed skylights.

Laouadi and Atif (2001) completed a numerical study on the heat transfer by steady-state laminar natural convection within multi-layer domes with uniform spacing. These models assumed heating from the above. They were able to develop correlations for heat transfer as a function of both the dome shape and the gap spacing between the layers. They define the term, δ as the dimensionless gap spacing between dome layers. By performing numerical analysis of both, the low profile and fully hemispherical domes both with various values of δ , they were able to reach the following conclusions: (1) Convection heat transfer is more that 10% higher for hemispherical domes as compared to low profile domes with

small values of δ (<0.1) and (2) convection heat transfer is more than 100% higher for hemispherical domes as compared to low profile domes with large values of δ (>0.3). These results are related to the flow patterns they observed in this analysis. For fully hemispheric domes, the flow patterns were consistently in a form of single cell for all values of δ . However, for low profile domes, large gap spaces produced two cells. Finally, their research also suggests the existence of a critical gap space for each dome analyzed. The convection heat transfer increases to a maximum at this critical value of δ and then decreases upon further increases of the gap spacing.

Also relevant are the assumptions, boundary conditions, and modeling techniques employed by Laouadi and Atif (2001). The primary numerical assumptions employed are as follows: the fluid is incompressible, the buoyancy-driven flow within the dome gap is laminar, the physical properties of the fluid are constant except for density, and fluid density is given by the Boussinesq's approximation. The boundary conditions assume no-slip and uniform temperature conditions at the dome walls. Furthermore, symmetry and adiabatic conditions can be employed at the axis of revolution and the edges respectively. Finally, most relevant to the current study the observation made by Laouadi and Atif (2001) with regards to the case when the interior dome wall is hotter than the exterior. This case, which was not the major focus of their research, yielded unsteady, periodic flow, particularly for small values of the gap spacing.

The results of numerical modeling were compared to numerical research of Garg (1991) and to correlation developed by Raithby and Hollands (1975), in which experimental data of Bishop (1965) was used. The results of Laouadi and Atif (2001) are in good agreement with numerical results obtained by Garg (1991). However, only horizontal orientation of the dome was investigated in (2001).

4. BASIC PARAMETERS AND GEOMETRICAL CONSIDERATION FOR DOMED SKYLIGHTS

Figure 1 shows simplified view of a domed skylight glazing system with uniform spacing between two concentric spheres. The basic geometrical parameters (dimensions and radii) as defined for a domed skylight glazing cavity are:

- R_i and R_o – inner and outer radii of spheres;
- H – Curvature of the glazing cavity;
- L – gap spacing between spherical surfaces of glazing cavity;
- Aspect Ratio $A_L = H/L$;
- Aspect Ratio $A_H = H/R_i$.

The parameter $A_H = 1$ for a fully hemispherical domed skylight, $0 < A_H < 1$ for low profile domed skylights and $A_H = 0$ for concentric disks.

Domed skylights often incorporate non-uniform gap widths and these will be presented later in this report.

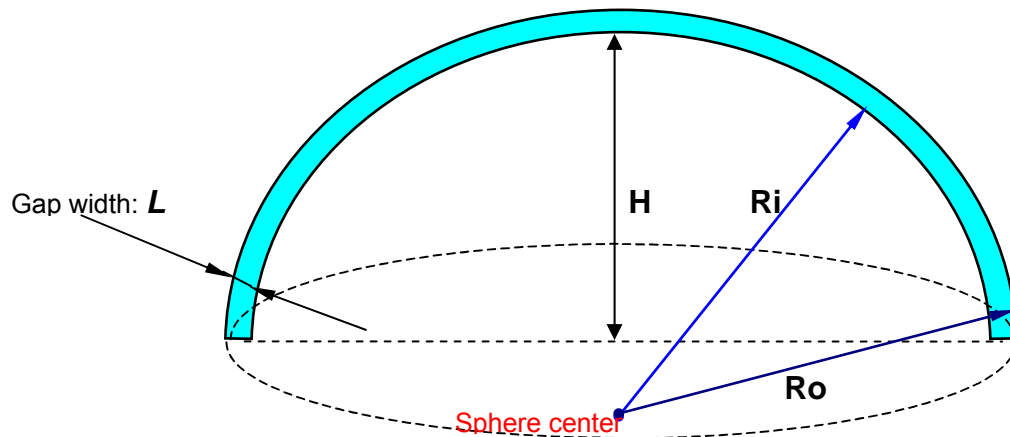


Figure 1. Schematic of Domed Skylight Glazing System with Uniform Gap Width

Table 1 presents the parameters for the example domed skylight for the 3-D heat transfer simulation in the range of Raleigh number from $Ra = 4,000$ to $Ra = 80,000$.

Table 1. Matrix of Glazing Cavity Configurations and Sizes

| Inner radius $R_i = 0.8$ m | | | | Inner radius $R_i = 1.2$ m | | | |
|--------------------------------------|-------------|-------------|-------------|----------------------------|-------------|-------------|-------------|
| $A_H = 1$ | $A_H = 1$ | $A_H = 0.5$ | $A_H = 0.5$ | $A_H = 1$ | $A_H = 1$ | $A_H = 0.5$ | $A_H = 0.5$ |
| $L = 16$ mm | $L = 25$ mm | $L = 16$ mm | $L = 25$ mm | $L = 16$ mm | $L = 25$ mm | $L = 16$ mm | $L = 25$ mm |
| Tilt angle from horizontal direction | | | | | | | |
| 20° | 90° | 20° | 90° | 20° | 90° | 20° | 90° |

In order to develop an effective 3-D model of heat transfer in a gap of the domed skylight, it is necessary to perform mesh study first. The initial study involved the diameter of the dome of $D = 0.6$ m and gap spacing of $L = 0.025$ m. Figure 2 shows 3-D mesh model of fully hemispherical domed skylight glazing cavity created from T-Grid elements (detailed description of T-Grid elements is provided in FDI (2003)). The details of boundary layer mesh within glazing cavity model are shown in Figure 3.

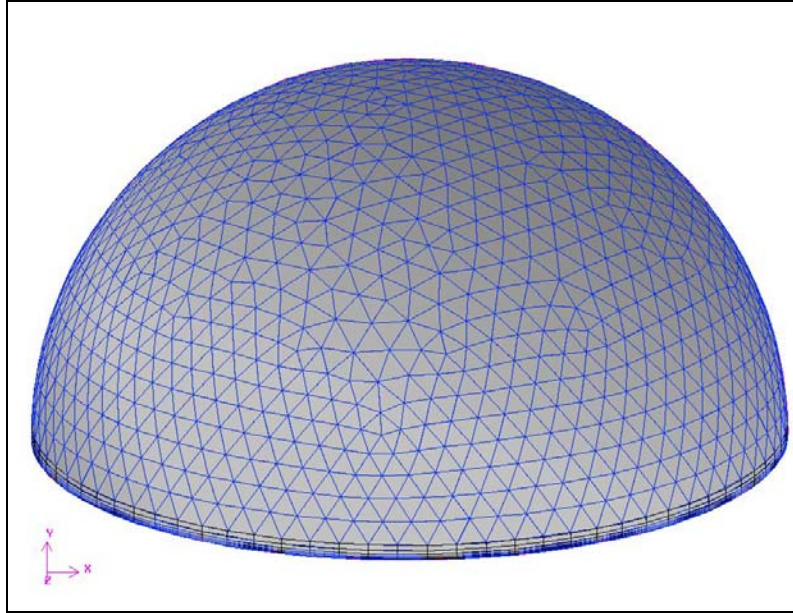


Figure 2. T-Grid Mesh of the Hemispherical Glazing Cavity of a Domed Skylight. Outer Diameter is 0.6 m; Glazing Gap Spacing is 0.025 m.

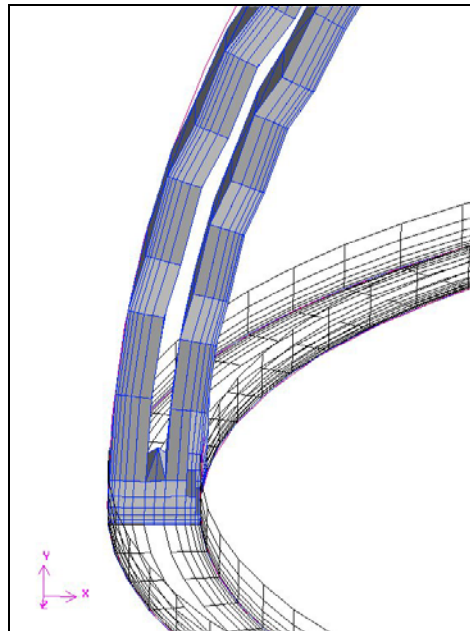


Figure 3. Boundary Layer Mesh Structure of 3-D Glazing Cavity Formed by Two Concentric Spheres

4.1 Results and Validation of the numerical model

A Fluent segregated solver (FDI 2003) was used with the following settings:

- Implicit equation formulation,
- Steady state model,
- Laminar viscous model;
- Solution controls: under-relaxation factors (RF) for all equations (variables) were defined with default settings and for energy equation as $RF = 0.98$,
- Method of discretization: pressure equation – PRESTO; pressure-velocity coupling – SIMPLEC; momentum – First Order; energy – First Order Scheme,
- Thermo-physical properties of air were treated as constants and were evaluated at the temperature of 0°C ,
- Boussinesq approximation was used in viscous laminar model.

With these settings, for this 3-D model the solution reached convergence after approximately 120 iterations.

For the purposes of comparison, the following model was created; the case when the exterior dome wall is at higher temperature than the interior one because the prior published work included this configuration (Laouadi and Atif 2001). Predicted temperature and velocity fields in the cavity for the heated outside wall case are shown in Figure 4 and Figure 5. From these distributions it is obvious that convection does not play significant role in the top part of the cavity, where the majority of heat transfer happens by conduction. This would mean that for the opposite heat flux direction, the heat transfer rate should increase.

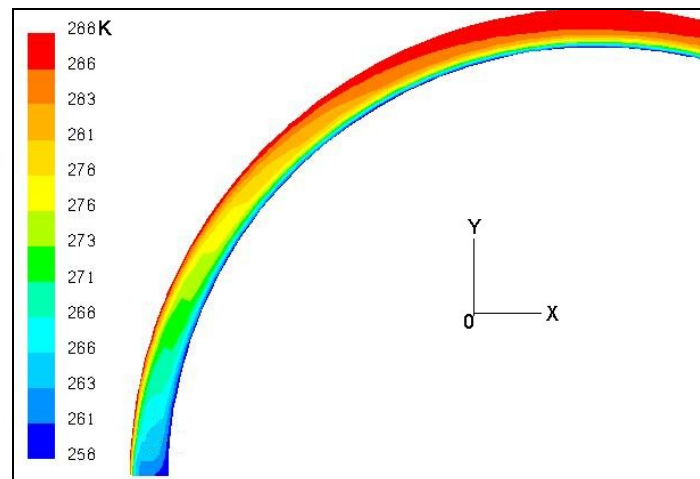


Figure 4. Temperature Distribution in a Centerline Cross-Section of the 3-D Glazing Cavity Formed by Two Concentric Spheres. Heat Flow Direction is Down. $Ra = 68,000$.

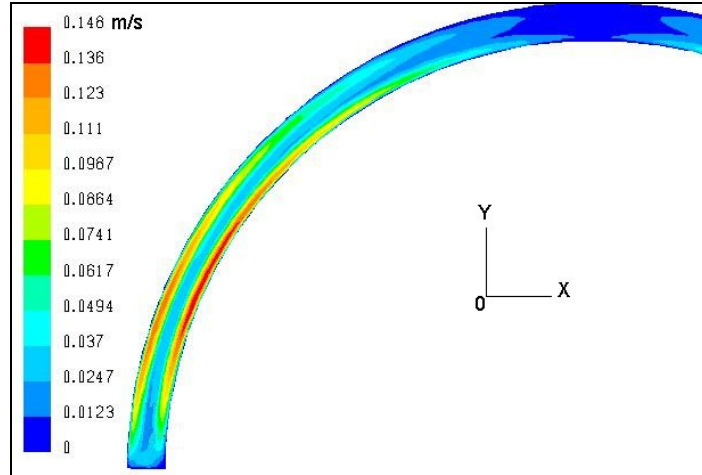


Figure 5. Velocity Field Magnitude in a Centerline Cross-Section of the 3-D Glazing Cavity Formed by Two Concentric Spheres. Heat Flow Direction is Down. $Ra = 68,000$.

The results of this modeling are compared with those published in the literature about heat transfer in concentric spheres by Raithby and Hollands (1975) and Garg (1991) and with numerical modeling results of Laouadi and Atif (2001). Raithby and Hollands (1975) developed a correlation for the Nusselt number under steady state conditions. The correlation is expressed as follows:

$$Nu = \max \left\{ 1, c(Ra^x)^{\frac{1}{4}} \right\} \quad (1)$$

Where:

$c =$ Empirical coefficient based on the experimental data of Bishop et al. (1965);

$Ra^x =$ Modified Rayleigh number.

Modified Rayleigh number is expressed as:

$$Ra^x = \frac{Ra \cdot 0.5 \cdot \delta}{\left[(1 + \delta)^{-0.6} + (1 + \delta)^{0.8} \right]^{\frac{1}{5}}}, \quad (2)$$

Where:

$\delta = L/R_i$

$\delta =$ Dimensionless gap spacing width (see Figure 1).

Dimensionless gap spacing for this model was $\delta = 0.091$.

According to Laouadi (2001) the coefficient c may also be expressed as a function of gap spacing δ for hemispherical domes using the following relation:

$$c = 0.7493 - 0.2461 \cdot \delta + 0.1129 \cdot \delta^2 - 0.0162 \cdot \delta^3 \quad (3)$$

The comparison between numerical modeling results of this study and calculations according to correlation (1) is presented in Figure 6 in terms of dimensionless convection heat transfer rate (i.e. Nusselt number, Nu). The maximum difference between compared values is 4.6% (for $Ra = 90,500$), which is within the accuracy limits of the correlation. Thus, the proposed numerical procedure and 3-D model results show complete conformity with results of existing published studies.

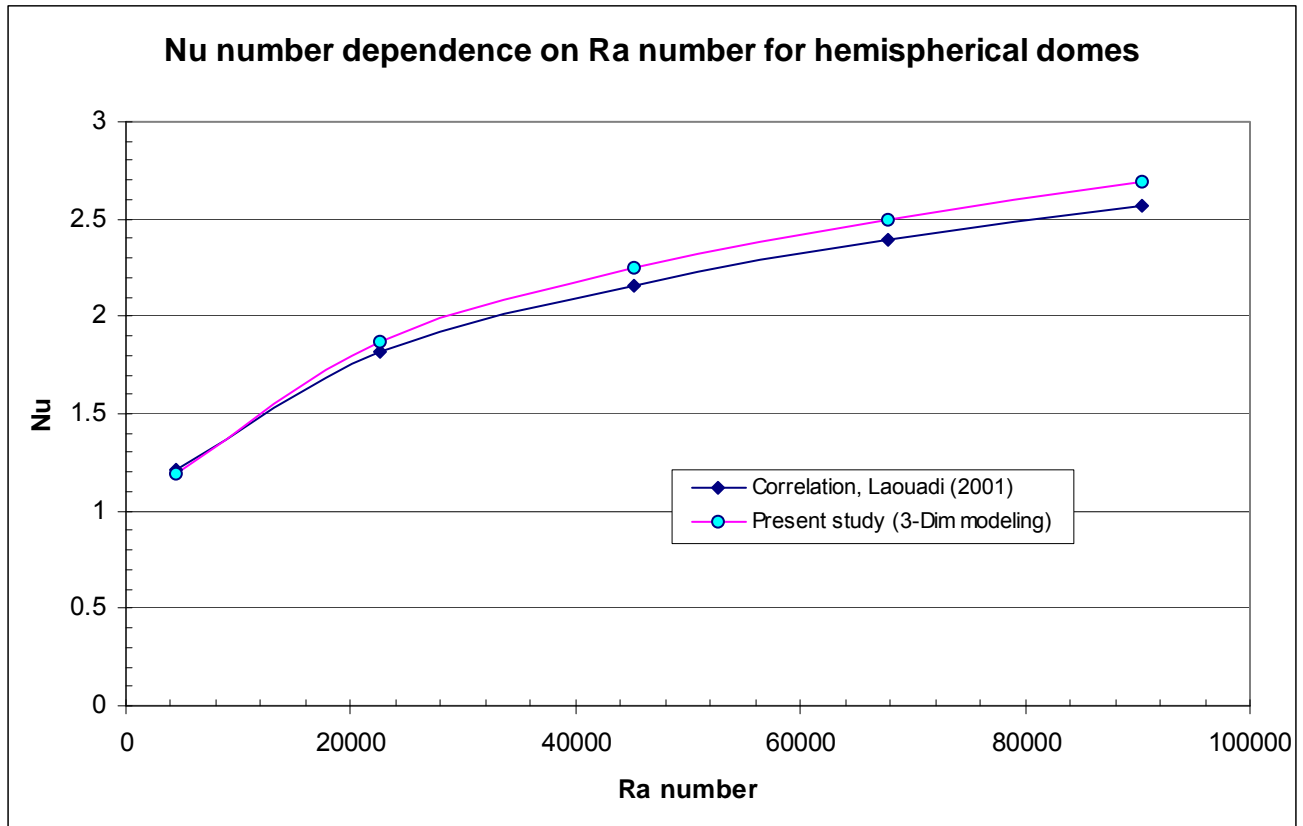


Figure 6. Comparison of Numerical Model with Correlation from Raithby and Hollands (1975).

However, for the prediction of nighttime thermal performances of domed skylights (also known as “Winter Standard Conditions”, which is used for determining U-factors in NFRC rating) it is necessary to model laminar convection in domed skylight glazing cavity heated from the indoor facing surface (i.e., heat flow up). In this case, in the top region of the glazing cavity, the flow regime is similar to the convection heat transfer in the horizontal rectangular cavity heated from the bottom. Because of the expected multi vortices (or multi-cell) convection regime and flow pattern and based on previous studies (Yang 2004), only

full 3-D modeling can be used in this case. Predicted temperature field in the domed glazing cavity for the heat flow up case is shown in Figure 7.

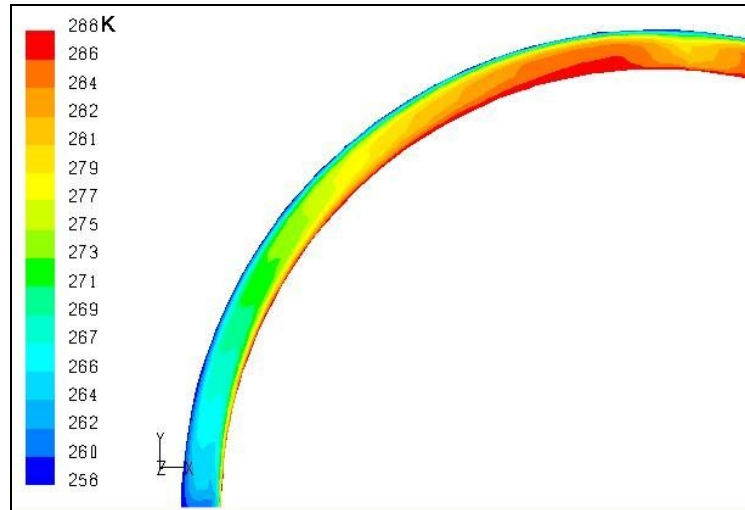


Figure 7. Temperature Distribution in a Centerline Cross-Section of the 3-D Glazing Cavity Formed by Two Concentric Spheres. Heat Flow Direction is Up. $Ra = 68,000$.

The comparison of convection heat transfer rates between the two cases, heat flow up and heat flow down, is given in Figure 8. Nu increases by 5% on average for the case of cavity heated from inside surface (heat flow up) when comparing to the cavity heated from outside (heat flow down).

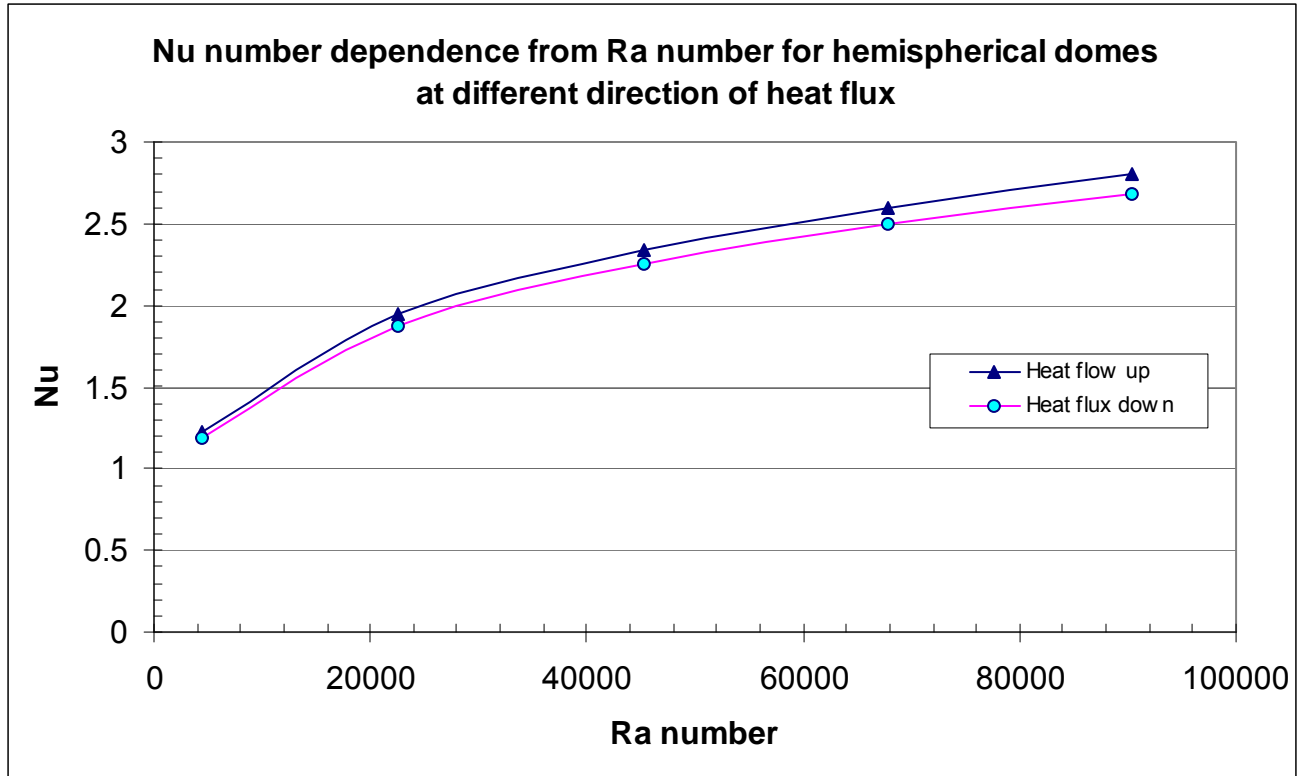


Figure 8. Comparison of Heat Transfer Rates for the 3-D Glazing Cavity Formed by Two Concentric Spheres with Different heat Flow Directions.

4.2 Summary

- The 3-D numerical model of natural convection heat transfer in domed skylight glazing cavity formed by two concentric spheres, is developed. The following geometric parameters were employed in order to compare to published results; diameter $D_o = 0.78$ m and spacing gap width $L = 0.0325$ m,.
- The 3-D numerical model results of heat transfer in domed skylight glazing cavity formed by two concentric spheres agreed well with the published studies, consisting of experimental and numerical results. The difference between compared Nusselt numbers is less than 4.6% for the case of cavity heated from outside (heat flow down).
- The 3-D numerical modeling and assumptions can be used for simulation of convection heat transfer in a full range of domed skylight glazing cavities under consideration.

4. ANALYSIS OF DOMED SKYLIGHT GLAZING CONFIGURATIONS AND GEOMETRY

In this section, realistic domed skylight geometry and configuration are analyzed (Vistawall 1994, BOCA 1997, ODL 1998, Crystalite 2006). These skylights include double and triple domed units constructed from sheets of acrylic or polycarbonate. The purpose is to select representative products for this research project.

Three main configurations, representative of domed skylights manufactured and sold in North America, are considered;

- 1) Type-A: Double domed glazing with both surfaces curvilinear
- 2) Type-B: Double domed glazing with one curvilinear and one flat surface
- 3) Type-C: Triple domed glazing with two curvilinear and one flat surface

The schematic of the three configurations are shown in Figure 9 .

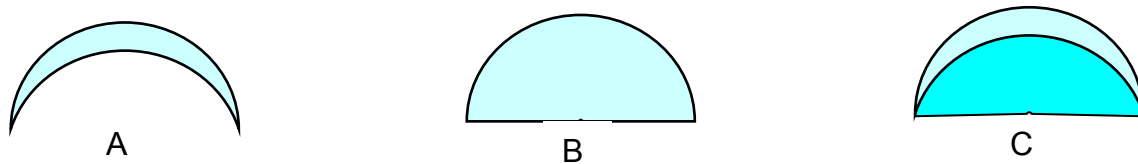


Figure 9. Types of Domed Skylight Glazing Configurations.

Because of the substantial differences in geometry, it is anticipated that one generalized convection heat transfer correlation couldn't be derived for Type-A and Type-B of domed skylight glazing cavity and that is why they will be considered separately. Convection heat transfer in the Type-C glazing can be derived as combined heat transfer through the glazing of Type-A and Type-B and will not be studied separately.

4.1 Domed Skylight Glazing Type-A

For this glazing type and for the purpose of better generalization, it is assumed that dome surfaces are close enough to two intersecting spherical surfaces. Therefore, the three main dome dimensions are:

- The diameter of the glazing base: $\varnothing = 2r$,
- The height of the dome: H ;
- The maximum thickness of the gap between dome layers, d .

These dimensions could be obtained from drawings or by measuring physical skylight samples. Figure 10 shows the geometry and four main parameters of the Type-A glazing system.

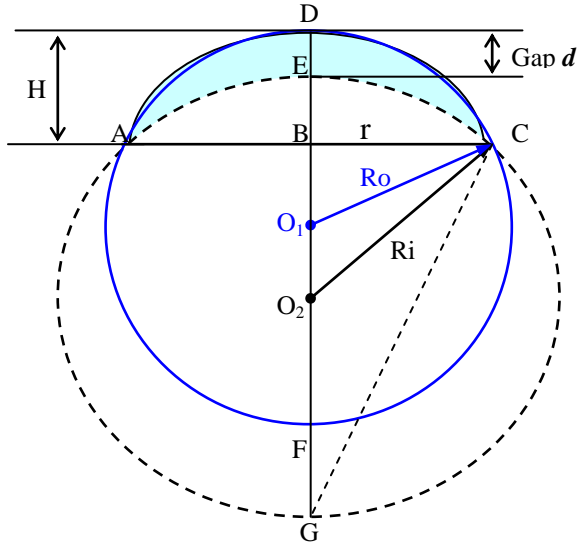


Figure 10. Geometry of the Double Domed Skylight Glazing System with Non-Uniform Gap Width.

The basic model dimensions can be expressed through the use of the well-known geometrical relations:

$$r^2 = BC^2 = BD \cdot BF = H \cdot (2 \cdot R_0 - H) \quad (4)$$

$$r^2 = BE \cdot BG = (H - d) \cdot (2 \cdot R_i - H + d) \quad (5)$$

Where:

$$r = \frac{\emptyset}{2} = \frac{AC}{2}$$

$r =$ radius of the glazing

$R_i =$ radius of the inner sphere of the domed skylight glazing,

$R_o =$ radius of the outer sphere of the domed skylight glazing.

From (4) and (5) and Figure 10, it follows:

$$R_i = \frac{\frac{r^2}{(H-d)} + H - d}{2} \quad (6)$$

$$R_o = \frac{\frac{r^2}{H} + H}{2} \quad (7)$$

$$O_1O_2 = R_i - R_o + d \quad (8)$$

Where:

O_1O_2 = distance between centers of inner and outer spheres.

Equations (6) to (8) give all necessary information for creating numerical model from specified domed skylight glazing system dimensions.

From the review of typical domed skylights used in buildings in North America and from the standard NFRC size we can deduce the following range of the main domed skylight glazing dimensions in this study:

- The range of glazing base diameter (\emptyset) is from 0.6 m to 1.2 m;
- The ratio of dome height to glazing base diameter (H/\emptyset) is from 0.12 to 0.3;
- The range of maximum thickness of the gap (d) is from 0.05 m to 0.07 m.

Table 2 presents domed skylight parameters selected for 3-D heat transfer simulation in the range of Raleigh number from $Ra = 11,000$ to $Ra = 70,000$ (temperature difference from 5K to 30K).

Table 2. Matrix of Dome Skylight Glazing Cavity Configurations and Sizes.

| Glazing base diameter $\emptyset = 0.6$ m | | | | | | | | Glazing base diameter $\emptyset = 1.2$ m | | | | | | |
|---|---------------------|---------------------|---------------------|----------------------|---------------------|---------------------|---------------------|---|---------------------|---------------------|---------------------|---------------------|---------------------|---------------------|
| $H/\emptyset = 0.1$ | $H/\emptyset = 0.2$ | $H/\emptyset = 0.3$ | $H/\emptyset = 0.3$ | $H/\emptyset = 0.15$ | $H/\emptyset = 0.3$ | $H/\emptyset = 0.3$ | $H/\emptyset = 0.3$ | $H/\emptyset = 0.15$ | $H/\emptyset = 0.3$ | $H/\emptyset = 0.3$ | $H/\emptyset = 0.3$ | $H/\emptyset = 0.3$ | $H/\emptyset = 0.3$ | $H/\emptyset = 0.3$ |
| $d = 50$ mm | $d = 50$ mm | $d = 50$ mm | $d = 75$ mm | $d = 50$ mm | $d = 50$ mm | $d = 50$ mm | $d = 75$ mm | $d = 50$ mm | $d = 50$ mm | $d = 50$ mm | $d = 50$ mm | $d = 75$ mm | $d = 50$ mm | $d = 75$ mm |
| Tilt angle from horizontal direction | | | | | | | | | | | | | | |
| 90° | 20° | 90° | 20° | 90° | 20° | 90° | 20° | 90° | 20° | 90° | 20° | 90° | 20° | 90° |

4.2 3-D Numerical Modeling of Convection Heat Transfer in Type-A Glazing Cavity.

4.2.1 Description of boundary conditions and numerical model.

Figure 11 shows geometry and boundary conditions for the 3-D numerical model of Type-A domed skylight glazing cavity that was created using geometrical parameters obtained from equations (6) to (7). Two isothermal walls with temperature T_h and T_c are modeled as the inside (hot) and outside (cold) spherical surfaces of the glazing cavity.

For the simulation of natural convection heat transfer in a cavity we used a laminar viscous model with Boussinesq approximation. Thermo-physical properties of air were treated as constants and were evaluated at the temperature of 0°C as the representative mean temperature in the glazing cavity.

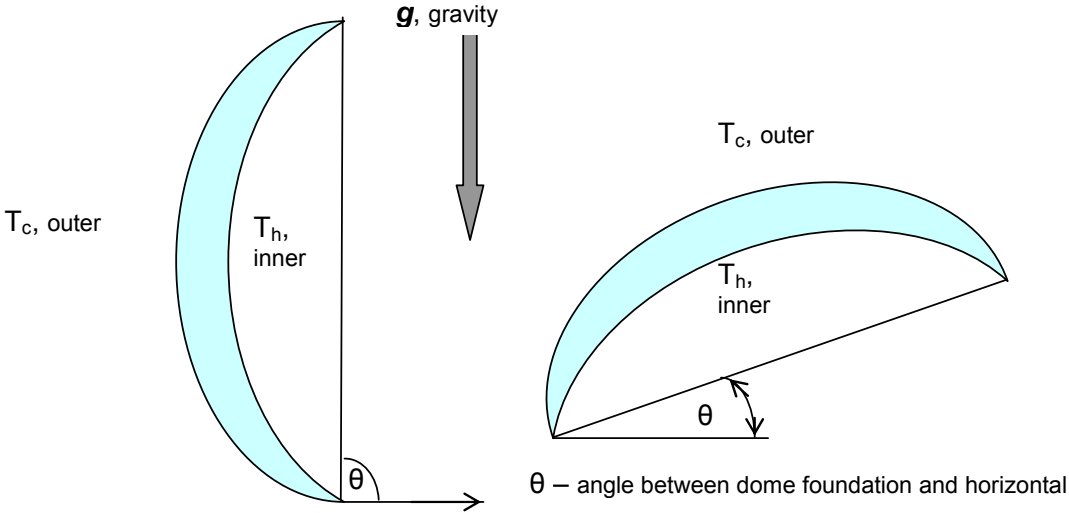


Figure 11. Orientation and Boundary Conditions for the Type-A Domed Skylight Glazing Cavity.

Figure 12 shows 3-D mesh of domed skylight glazing cavity Type-A with boundary layers created from T-Grid elements using Fluent software (FDI 2003).

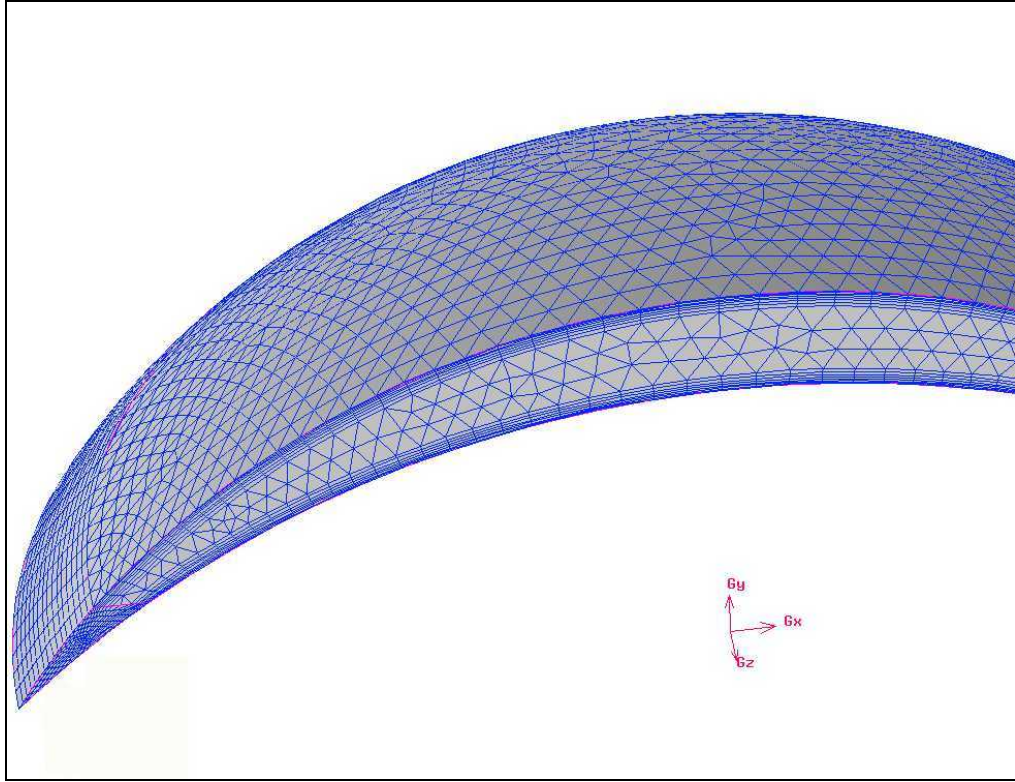


Figure 12. Numerical Mesh for the Type-A Domed Skylight Glazing Cavity.

4.2.2 Results and discussion

Predicted temperature and velocity fields in the Type-A domed skylight glazing cavity ($\varnothing = 60$ cm, $H/\varnothing = 0.3$, maximum gap $d = 50$ mm) in vertical position ($\theta = 90^\circ$) are shown in Figure 13 and for tilt orientation ($\theta = 20^\circ$) are shown in Figure 14.

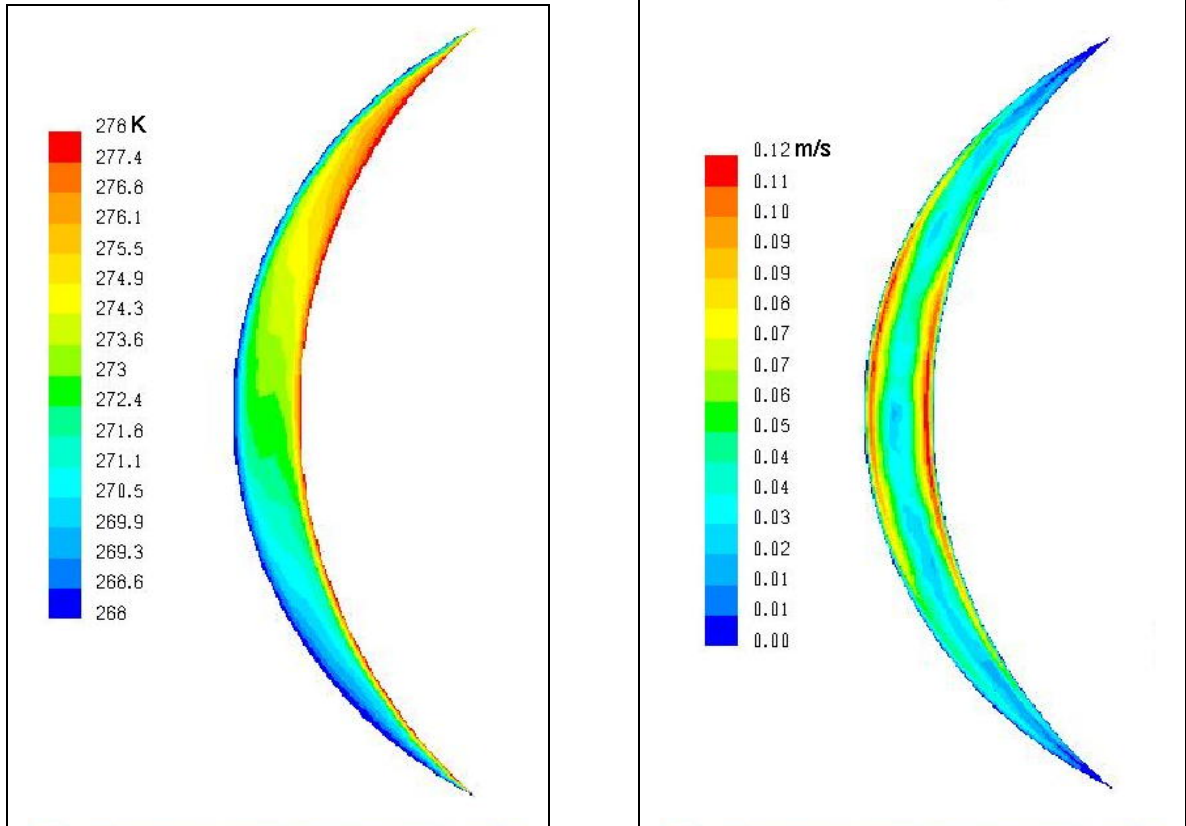


Figure 13. Temperature and Velocity Magnitude Distributions in a Symmetry Plane of the Type-A Domed Skylight Glazing Cavity at Vertical Orientation. $Ra = 23,000$ ($\Delta T = 10K$).

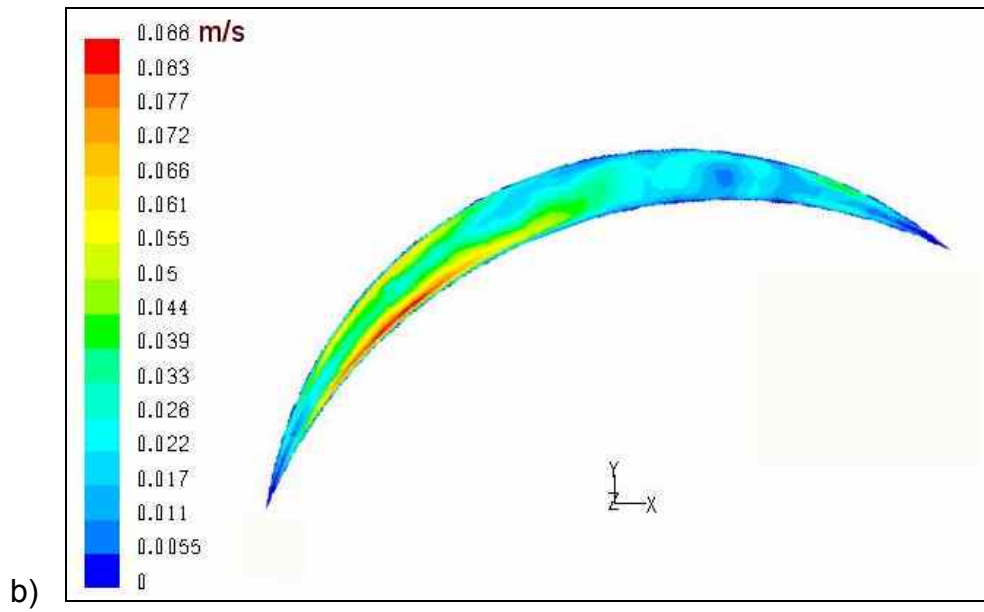
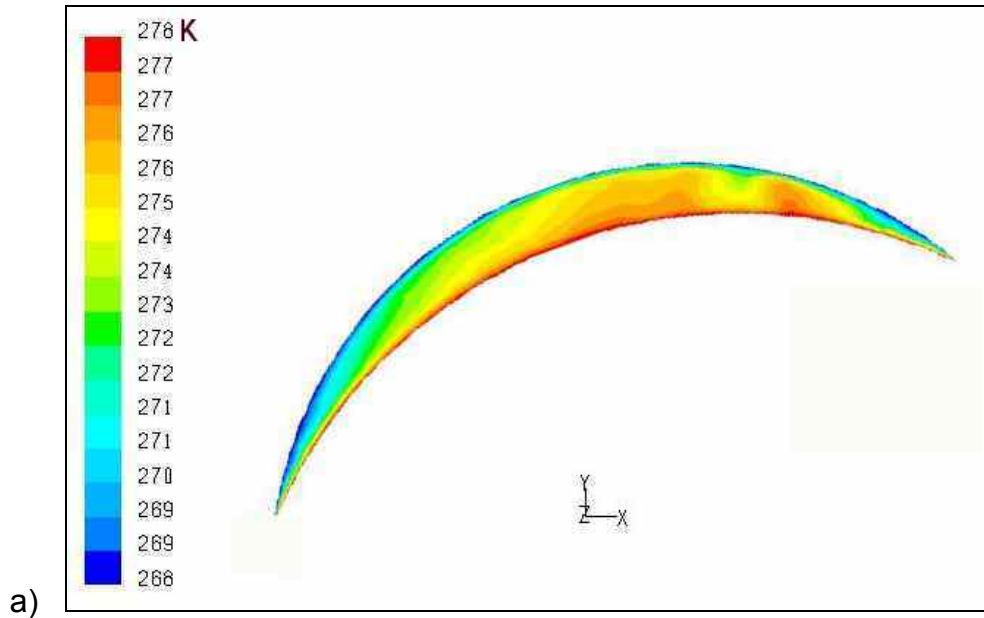


Figure 14. Temperature (a) and Velocity Magnitude (b) Distributions in a Symmetry Plane of the Type-A Domed Skylight Glazing Cavity at a tilt angle $\theta = 20^\circ$. $Ra = 23,000$ ($\Delta T = 10K$).

Modified Nusselt number for cavities with irregular gap and curved walls

Nusselt number, Nu , is dimensionless average heat flux on the indoor cavity wall and usually applies to convection heat transfer rate in enclosures. In general Nu is ratio of the heat flux due to combined convection and conduction to the heat flux due to conduction only under the same conditions. For pure conduction it follows that $Nu = 1$. For rectangular cavities Nu is expressed as follows:

$$Nu = \frac{q_{conv}}{q_{cond}} = \frac{q_{conv}}{\frac{k \cdot \Delta T}{L}} \quad (9)$$

Where:

q_{conv} = heat flux caused by combined convection and conduction heat transfer in a cavity;

q_{cond} = heat flux caused by conduction only heat transfer in a cavity;

L = characteristic size of a cavity in the direction of the heat flux, usually it is the thickness of the cavity gap;

k = thermal conductivity at of air at the average temperature in the cavity;

ΔT = temperature difference between cavity walls.

However the Nu expression (9) is not applicable for cavities with irregular gap and curved walls as in the case of glazing cavity of domed skylights. Simulation results are summarized in Table 3 in terms of thermal conductance (surface to surface heat transmission) in domed glazing cavity models for selected configurations and parameters.

Table 3. Thermal Conductance C_{cond} for the 3-D domed glazing cavity.

| Glazing base diameter $\varnothing = 0.6$ m | | | | Glazing base diameter $\varnothing = 1.2$ m | | |
|--|-----------------------|-----------------------|-----------------------|---|-----------------------|-----------------------|
| $H/\varnothing = 0.1$ | $H/\varnothing = 0.2$ | $H/\varnothing = 0.3$ | $H/\varnothing = 0.3$ | $H/\varnothing = 0.15$ | $H/\varnothing = 0.3$ | $H/\varnothing = 0.3$ |
| $d = 50$ mm | $d = 50$ mm | $d = 50$ mm | $d = 75$ mm | $d = 50$ mm | $d = 50$ mm | $d = 75$ mm |
| Cavity Thermal Conductance C_{cond} , $W/(m^2K)$ | | | | | | |
| 2.93 | 3.02 | 2.84 | 2.08 | 2.75 | 2.76 | 1.81 |

As a comparison, the layer of still air with thickness of 50 mm has thermal conductance of 0.481 $W/(m^2K)$ and at thickness of 75 mm has thermal conductance of 0.321 $W/(m^2K)$ under the same temperature conditions.

The following expression, derived from the present numerical study expresses heat flux q_{cond} due to conduction on inside cavity surface with errors less than 3% for most cases in

comparing with numerical modeling of conduction heat transfer (Table 3) in domed skylight glazing cavity

$$q_{cond} = \frac{\beta \cdot k \cdot \Delta T}{\frac{d}{2}} \quad (10)$$

Where:

$$\beta = 2.784 + 3.0 \cdot \frac{d}{\varnothing} \quad (11)$$

β = Form-factor of Type-A dome skylight glazing cavity heat transfer;

k = thermal conductivity of air at average temperature in the cavity;

ΔT = Temperature difference between cavity walls;

d = Maximum thickness of the glazing gap.

Using equation (10) the modified Nusselt number, Nu_m for domed glazing cavity can be expressed as:

$$Nu_m = \frac{q_{conv}}{\frac{2 \cdot \beta \cdot k \cdot \Delta T}{d}} = \frac{d \cdot q_{conv}}{2 \cdot \left(2.784 + 3.0 \cdot \frac{d}{\varnothing} \right) \cdot k \cdot \Delta T} \quad (12)$$

All heat transfer results are summarized in Table 4 and Figure 15 to Figure 18.

Table 4. Nusselt vs. Raleigh number Dependence for Type-A Domed Skylight Glazing Cavities

| Glazing base diameter $\varnothing = 0.6$ m | | | | | | | | | Glazing base diameter $\varnothing = 1.2$ m | | | | | |
|---|--|------|------------------------|------|------------------------|------|------------------------|------|---|------|------------------------|------|------------------------|------|
| H/ \varnothing | H/ $\varnothing = 0.1$ | | H/ $\varnothing = 0.2$ | | H/ $\varnothing = 0.3$ | | H/ $\varnothing = 0.3$ | | H/ $\varnothing = 0.15$ | | H/ $\varnothing = 0.3$ | | H/ $\varnothing = 0.3$ | |
| $d =$ | 50 mm | | 50 mm | | 50 mm | | 75 mm | | 50 mm | | 50 mm | | 75 mm | |
| $\theta =$ | 90° | 20° | 90° | 20° | 90° | 20° | 90° | 20° | 90° | 20° | 90° | 20° | 90° | 20° |
| Ra | Nu number ($Nu = q_{conv} / q_{cond}$) | | | | | | | | | | | | | |
| 11300 | 1.14 | 1.19 | 1.14 | 1.17 | 1.12 | 1.14 | 1.28 | 1.33 | 1.07 | 1.13 | 1.08 | 1.12 | 1.24 | 1.27 |
| 22600 | 1.19 | 1.30 | 1.19 | 1.23 | 1.19 | 1.24 | 1.39 | 1.48 | 1.11 | 1.21 | 1.13 | 1.18 | 1.33 | 1.38 |
| 45200 | 1.26 | 1.47 | 1.26 | 1.29 | 1.28 | 1.35 | 1.55 | 1.63 | 1.18 | 1.29 | 1.18 | 1.25 | 1.45 | 1.52 |
| 67800 | 1.30 | 1.53 | 1.31 | 1.35 | 1.34 | 1.42 | 1.65 | 1.74 | 1.24 | 1.36 | 1.23 | 1.30 | 1.54 | 1.61 |

In Figure 15, modeling results in terms of modified Nu number are presented for two glazing cavities (glazing base diameter $\varnothing = 0.6$ m and $\varnothing = 1.2$ m) with the same parameter H/ \varnothing in vertical ($\theta = 90^\circ$) and tilted orientations ($\theta = 20^\circ$). From numerical results we can conclude that increasing base diameter of domed glazing cavity from 0.6 m to 1.2 m results in

decrease of convection heat transfer by about 8% on average. For tilted cavities the convection heat transfer is on the other hand 6-7% higher on average than for vertical cavities.

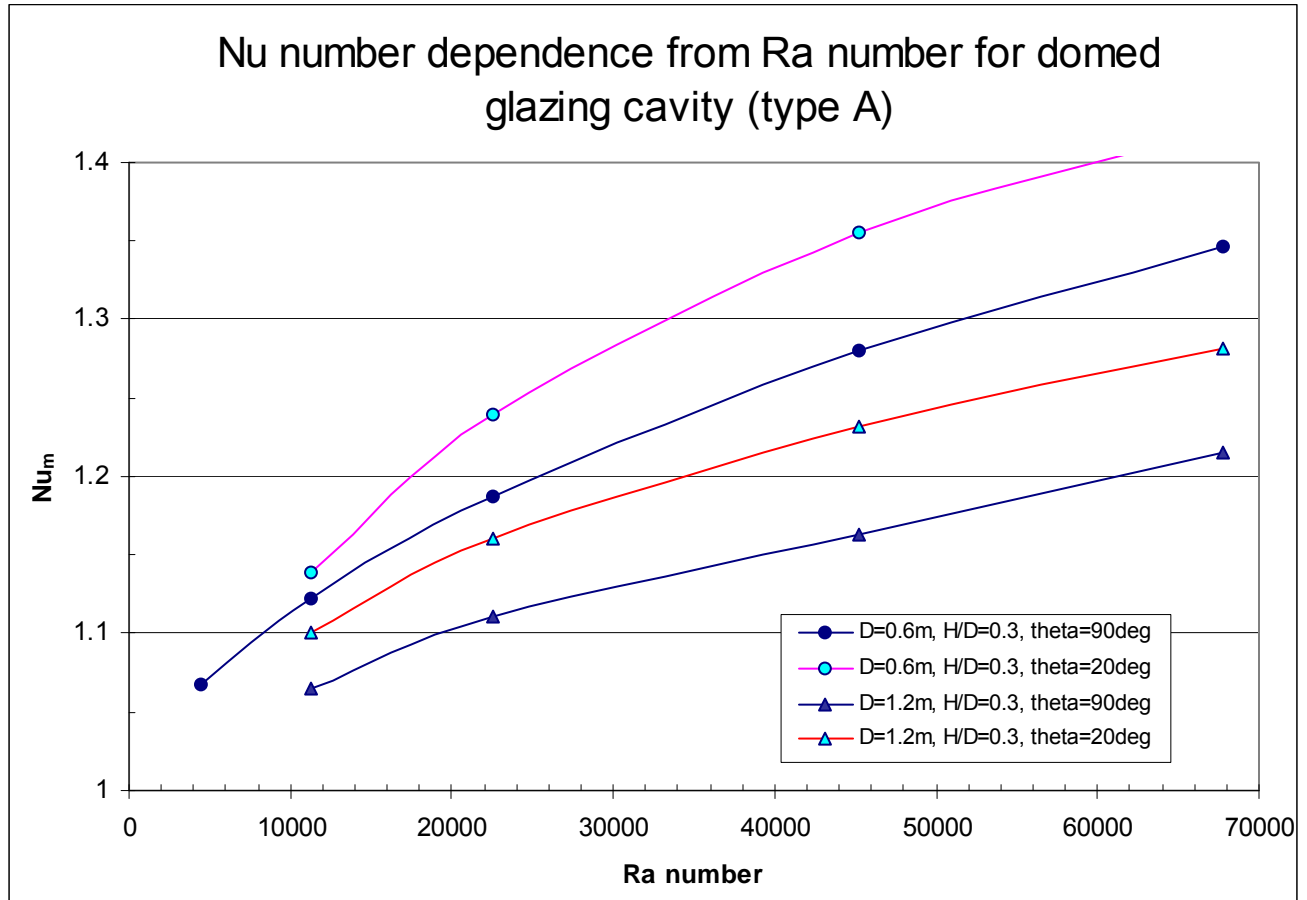


Figure 15. Comparison of Heat Transfer Rates for Two Type-A Domed Skylight Glazing Cavities (Glazing Base Diameter $\varnothing = 0.6$ m and $\varnothing = 1.2$ m).

Figure 16 shows comparison of heat transfer rates for domed skylight glazing cavities vs. rectangular cavities, typical of standard fenestration products, such as windows. The rectangular glazing cavity configuration was $H \times W \times L = 1\text{ m} \times 0.8\text{ m} \times 0.025\text{ m}$. Rectangular cavity gap of 0.025m is equal to the average gap of domed glazing cavity under the same boundary conditions, so to facilitate “apple to apple” type of comparison.

From this comparison we can conclude that the heat transfer rate (thermal conductance) of domed glazing cavities exceeds heat transfer rate of the rectangular glazing cavity by almost 200%.

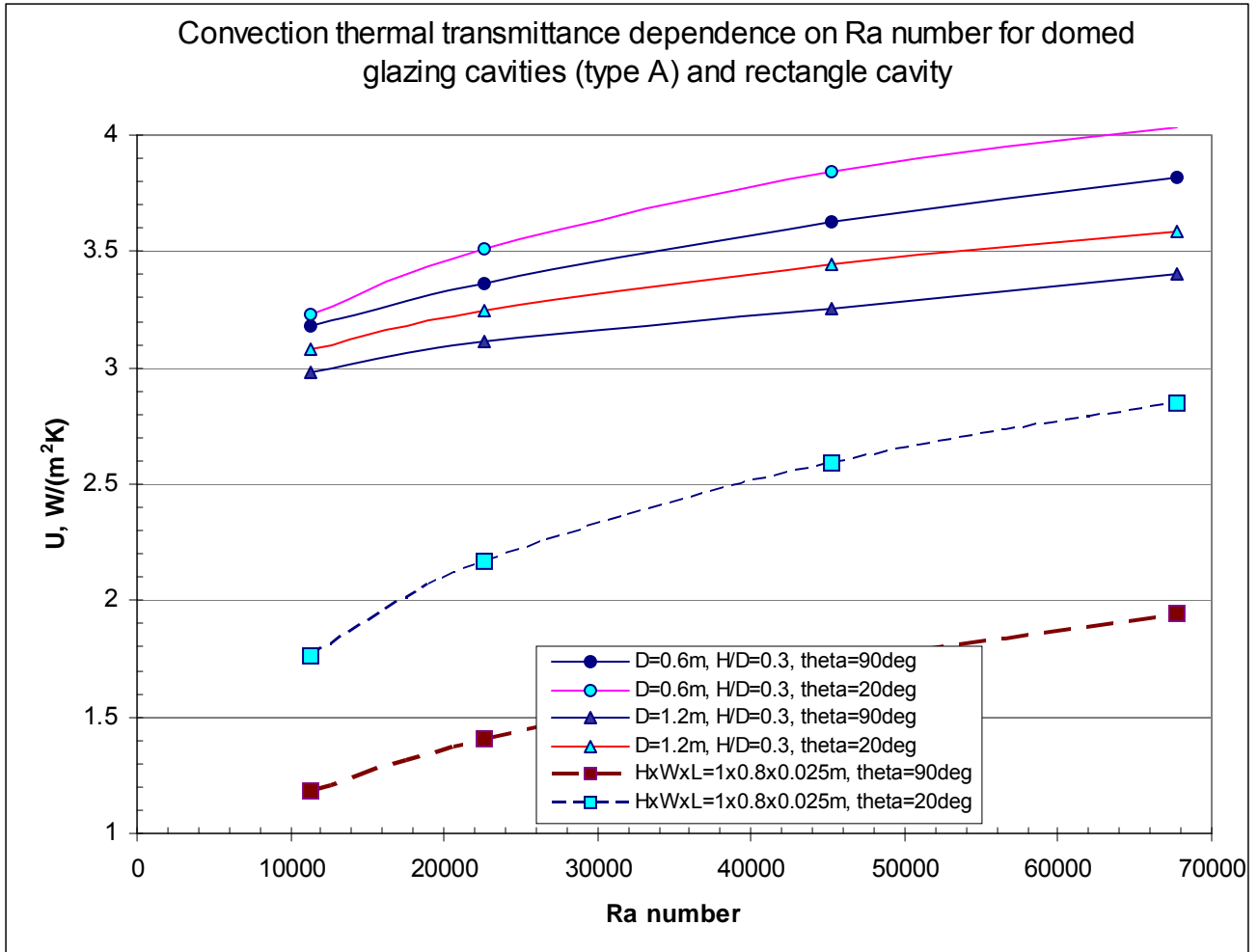


Figure 16. Comparison of Heat Transfer Rates for Type-A Domed Skylight Glazing Cavities and Rectangular Glazing Cavity ($H \times W \times L = 1\text{m} \times 0.8\text{m} \times 0.025\text{m}$).

Figure 17 shows heat transfer rates of domed skylight glazing cavities in vertical position ($\theta = 90^\circ$) with different parameter H/\varnothing (ratio of the dome height to the dome base diameter). The difference between predicted Nu does not exceed 3% and heat transfer rate for this case can therefore be considered as independent from parameter H/\varnothing .

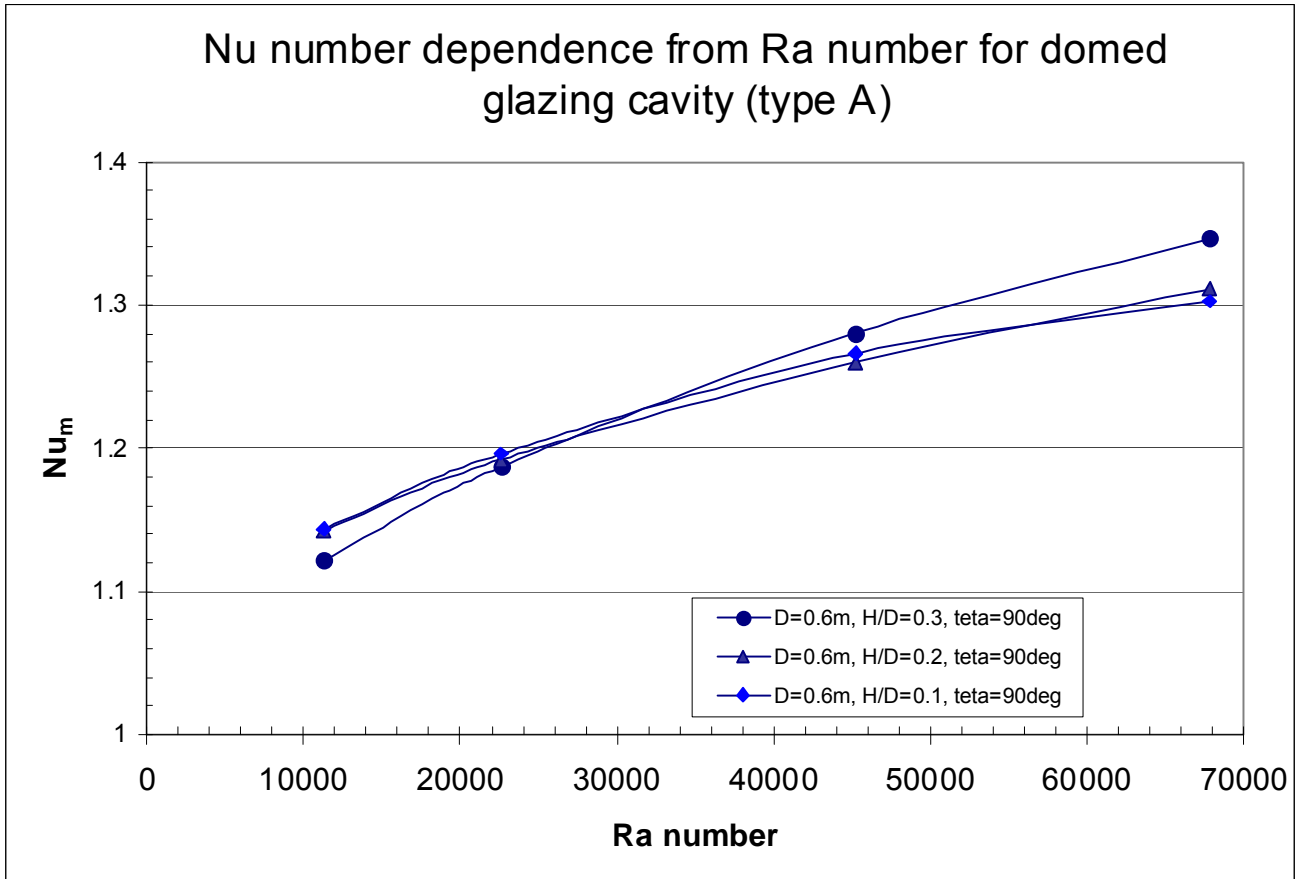


Figure 17. Heat Transfer Rate Comparison for Type-A Domed Skylight Glazing Cavities in Vertical Orientation with Different Parameter H/\varnothing .

More complicated Nu dependence was obtained in the case of tilted domed skylight glazing cavities with different parameter H/\varnothing as it is shown in Figure 18. The difference between predicted Nu for different parameter H/\varnothing in this case is up to 8%. The heat transfer rate for this case should be considered as dependent on the parameter H/\varnothing .

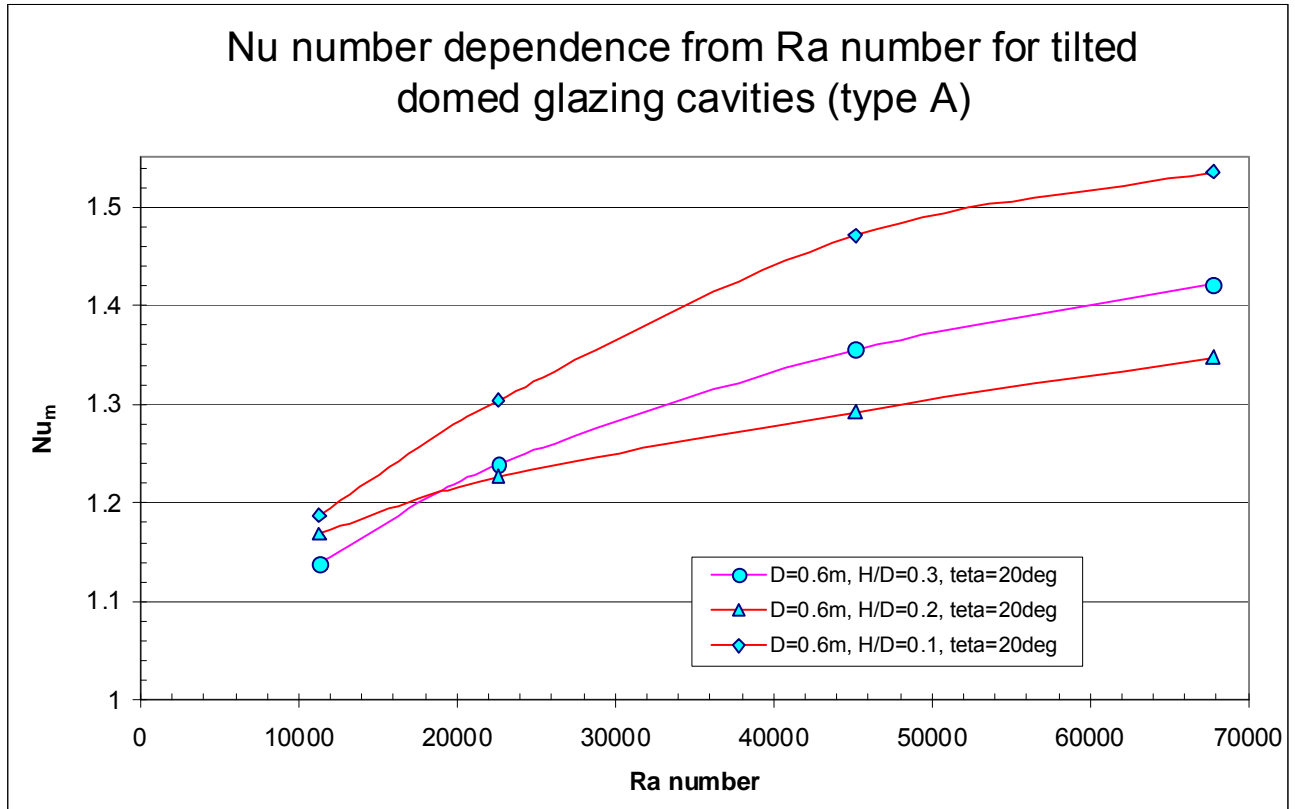


Figure 18. Heat Transfer Rate Comparison for Type-A Tilted Domed Skylight Glazing Cavities with Different Parameter H/\varnothing .

4.3 Heat transfer correlations for domed glazing cavity of a Type-A

4.3.1 Heat transfer correlations for Type-A domed skylight glazing cavities in vertical orientation

The following convection heat transfer correlations for Nu_m were derived from numerical modeling results for domed glazing cavities in vertical orientation ($\theta = 90^\circ$) as a function of Ra , d , and \varnothing :

a) Correlation for domed glazing cavities with maximum glazing cavity gap $d = 0.05\text{m}$ and glazing base diameter in the range from $\varnothing = 0.6\text{m}$ to $\varnothing = 1.2\text{m}$

$$Nu_{90} = 0.95 \cdot \left(0.01 \cdot Ra \cdot \frac{d}{\varnothing} \right)^{0.08} ; \quad d \leq 0.05 \text{ m} \quad (13)$$

$$Nu_{90} = 0.95 \cdot (0.00125 \cdot Ra)^{0.12} ; \quad d = 0.075\text{m} \text{ and } \varnothing \leq 0.6\text{m} \quad (14)$$

$$Nu_{90} = 0.95 \cdot (0.000625 \cdot Ra)^{0.13} ; \quad d = 0.075 \text{ m and } \varnothing = 1.2 \text{ m} \quad (15)$$

Where:

d = Maximum gap of glazing cavity, m;

\varnothing = Glazing base diameter, m.

Correlations (13) to (15) are used as endpoints in linear interpolation for determining modified Nu for specified Ra number in the range of maximum glazing gap from 0.05m to 0.075m and glazing base diameter from $\varnothing = 0.6$ m to $\varnothing = 1.2$ m.

Figure 19 and Figure 20 show how proposed correlations (13) to (15) compare with numerical modeling results. The maximum difference between correlations and modeling results is less than 4%.

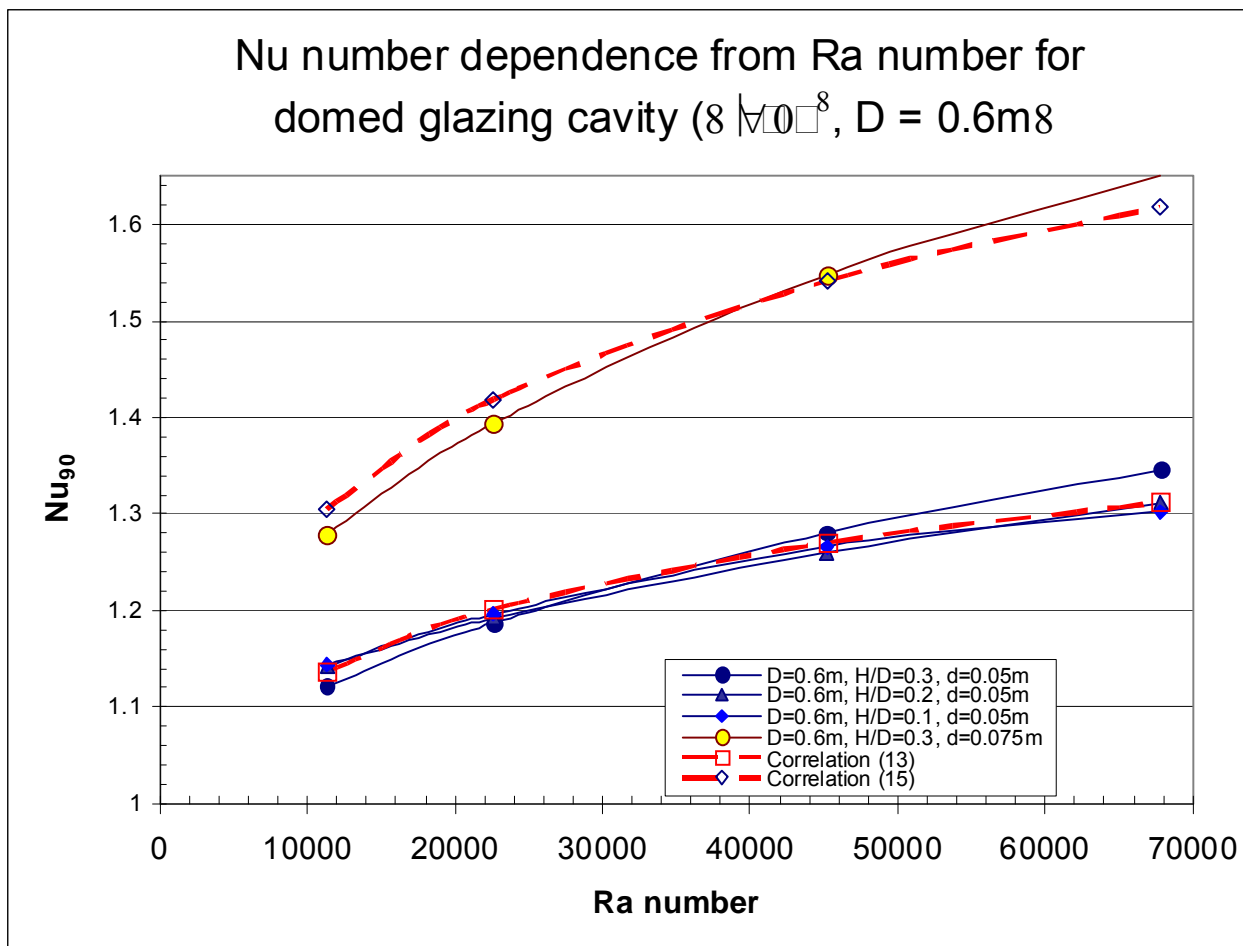


Figure 19. Comparison of Convective Heat Transfer Rates Predicted by Numerical Modeling and Correlations for Type-A Domed Glazing Cavity With Glazing Base Diameter $\varnothing = 0.6$ m.

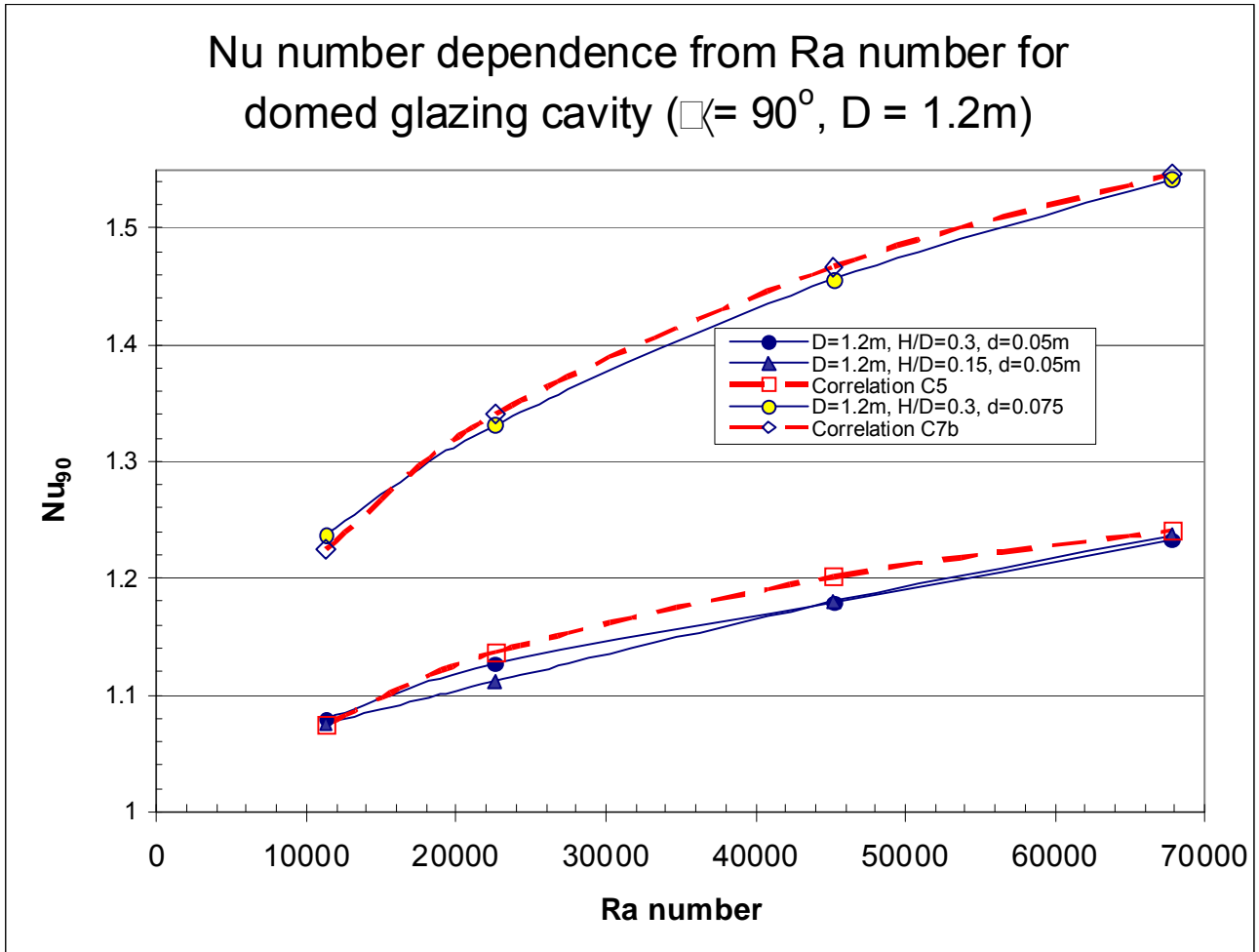


Figure 20. Comparison of Convective Heat Transfer Rates Predicted by Numerical Modeling and Correlations for Type-A Vertical Domed Glazing Cavity with Glazing Base Diameter $\varnothing = 1.2\text{ m}$.

Convective heat transfer coefficient is calculated from the Nu_m using the following relation:

$$h_c = Nu_m \frac{2 \cdot k}{d}$$

For intermediate values, linear interpolation can be used. The following is an example of the usage of correlations (13) to (15), when interpolation is applied.

Example of using correlations (13)-(15) for Nu number calculation:

Calculate Nu number for vertical domed skylight cavity at the following conditions:
 $Ra = 30000$; maximum cavity gap $d = 0.06\text{ m}$ and glazing base diameter $\varnothing = 1\text{ m}$.

Step 1. From equation (13) we find for values $Ra = 30000$, $d = 0.05\text{ m}$ and $\varnothing = 1\text{ m}$:

$$Nu_1 = 1.1798.$$

Step 2. From equation (15) we find for values $Ra = 30000$, $d = 0.075$ m and $\varnothing = 1.2$ m:

$$Nu_2 = 1.3906.$$

Step 3. From equation (14) we find for values $Ra = 30000$, $d = 0.075$ m and $\varnothing = 0.6$ m:

$$Nu_3 = 1.4676.$$

Step 4. Applying linear interpolation on parameter \varnothing to values Nu_2 and Nu_3 for diameter $\varnothing = 1.0$ m we find:

$$Nu_{2,3} = 1.4162.$$

Step 5. Applying linear interpolation on parameter d to values Nu_1 and $Nu_{2,3}$ for cavity gap $d = 0.06$ m we find:

$$Nu_m = 1.2743.$$

4.3.2 Heat transfer correlation for Type-A domed skylight glazing cavities in tilted orientation

The following convection heat transfer correlation for Nu_{20} was derived from numerical modeling results for domed glazing cavities in titled orientation ($\theta = 20^\circ$) as a function of Ra , d , and \varnothing :

$$Nu_{20} = Nu_{90} \cdot \left[1.03 + 2.3 \cdot 10^{-5} \cdot Ra \cdot \left(\log_{10} \left(\frac{H}{\varnothing} \right) + 0.7 \right)^2 \right];$$

$$d \leq 0.075 \text{ m}; \varnothing \leq 1.2 \text{ m}; H/\varnothing \leq 0.3 \quad (16)$$

Where:

Nu_{90} - Nusselt number for vertical orientation obtained using correlations (13) - (15)

Figure 21 show how proposed correlation (16) compare with numerical modeling results. The maximum difference between correlations and modeling results is less than 3%

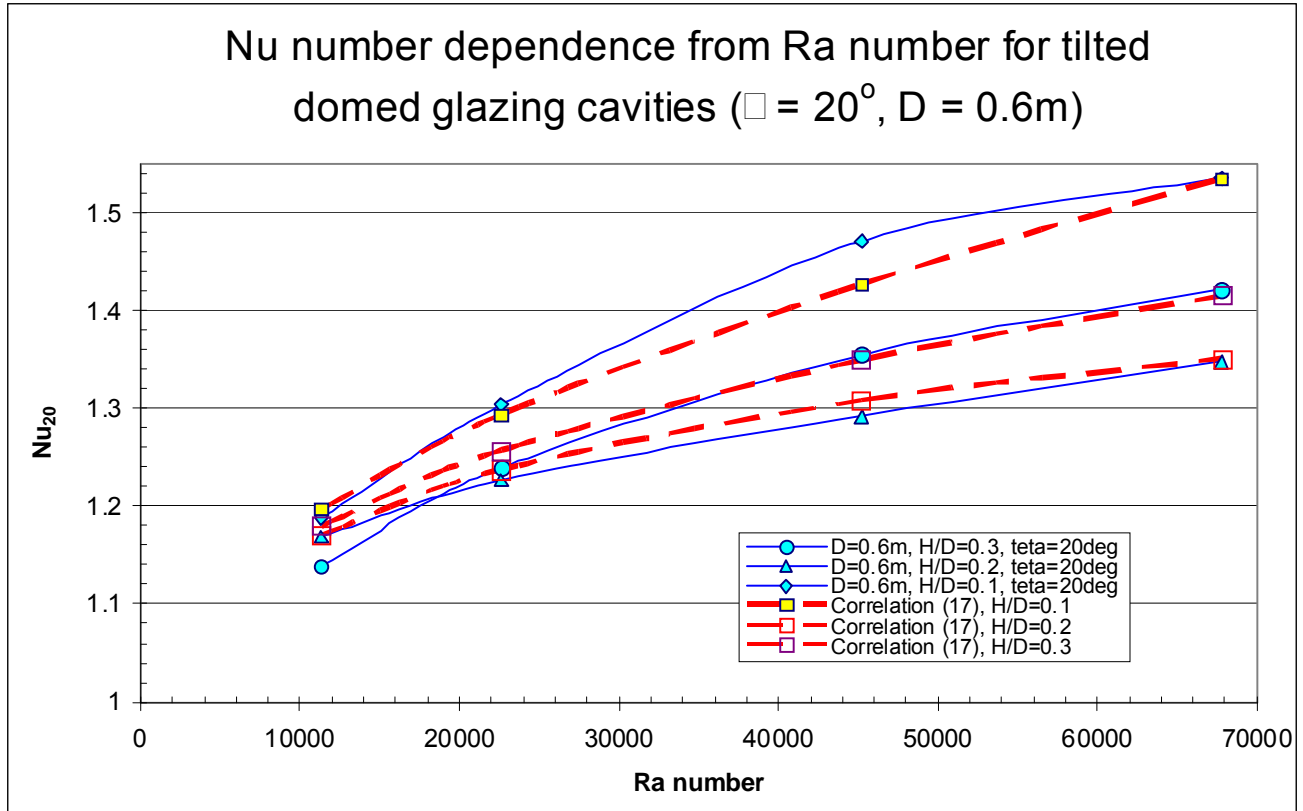


Figure 21. Comparison of Convective Heat Transfer Rates Predicted by Numerical Modeling and Correlations for Tilted Type-A Domed Skylight Glazing Cavity ($\theta=20^\circ$).

4.4 Domed Skylight Glazing Type-B

Type B domed skylight glazing cavity has one curved wall and other flat wall that is usually coinciding with skylight base as it is shown in Figure 22. For this glazing cavity type and for the purpose of better generalization, it is assumed that dome surfaces are close enough to an intersecting spherical and plane surfaces. Therefore, the two main dome dimensions are:

- The diameter of the glazing base: $\varnothing = 2r$;
- The height of the dome: H ;

These dimensions could be obtained from drawings or by measuring physical skylight samples.

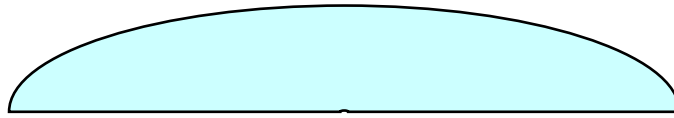


Figure 22. Cross-Section of the Type-B Domed Skylight Glazing Cavity.

Figure 23 shows the geometry and geometric parameters of the Type-B domed skylight glazing cavity, which will be used to generate 3-D numerical model.

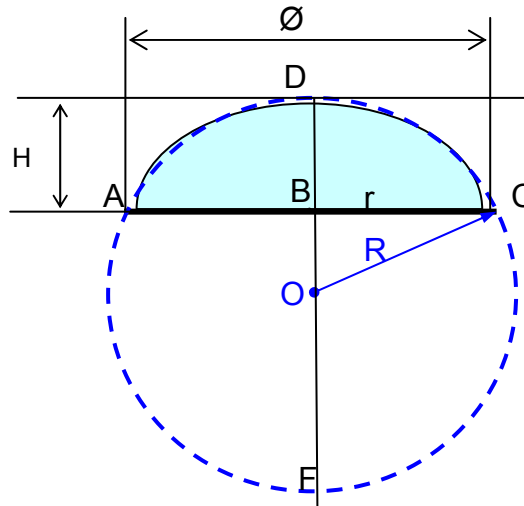


Figure 23. The Geometry of the Type-B Double Domed Skylight Glazing Cavity.

The basic model dimensions can be expressed through the use of the well-known geometrical relation:

$$r^2 = BC^2 = BD \cdot BF = H \cdot (2 \cdot R - H) \quad (17)$$

where:

$$r = \varnothing / 2 = AC / 2$$

r = radius of the glazing base

R = radius of the sphere,

H = Height of the dome

From equation (17) and Figure 36 it follows:

$$R = \frac{\frac{r^2}{H} + H}{2} \quad (18)$$

Equations (17) and (18) give all the necessary information for creating numerical model from the Type-B domed skylight glazing dimensions: H and \emptyset .

Table 5 presents domed skylight glazing cavity (type B) parameters selected for 3-D heat transfer simulation in the range of Raleigh number from $Ra = 11000$ to $Ra = 70000$ (temperature difference from 5K to 30K).

Table 5. Matrix of Type-B Domed Skylight Glazing Cavity Configurations and Sizes.

| Glazing base diameter $\emptyset = 0.6$ m | | | | | | Glazing base diameter $\emptyset = 1.2$ m | | | | | |
|--|------------|---------------------|------------|---------------------|------------|---|------------|---------------------|------------|---------------------|------------|
| $H/\emptyset = 0.1$ | | $H/\emptyset = 0.2$ | | $H/\emptyset = 0.3$ | | $H/\emptyset = 0.1$ | | $H/\emptyset = 0.2$ | | $H/\emptyset = 0.3$ | |
| Tilt angle from horizontal direction, θ | | | | | | | | | | | |
| 90° | 20° | 90° | 20° | 90° | 20° | 90° | 20° | 90° | 20° | 90° | 20° |

4.5 3-D Numerical Modeling of Convection Heat Transfer in Type-B Glazing Cavity.

4.5.1 Description of boundary conditions and numerical model.

Figure 24 shows geometry and boundary conditions for the 3-D numerical model of Type-B domed skylight glazing cavity that was created using geometrical parameters obtained from equations (17) and (18). Two isothermal walls with temperature T_h and T_c are modeled as the inside (hot) flat surface and outside (cold) spherical surface of the glazing cavity.

For the simulation of natural convection heat transfer in a cavity we used a laminar viscous model with Boussinesq approximation. Thermo-physical properties of air were treated as constants and were evaluated at the temperature of 0°C as the representative mean temperature in the glazing cavity.

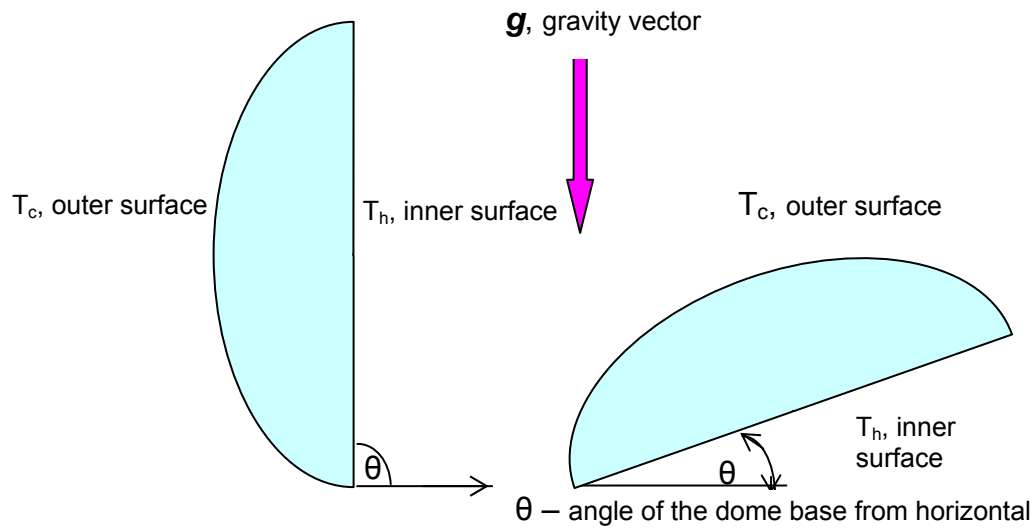


Figure 24. Orientation and Boundary Conditions for the 3-D Glazing Cavity Type-B.

Figure 25 shows 3-D mesh of domed skylight glazing cavity Type-B with boundary layers created using Fluent software (FDI 2000 and FDI 2003).

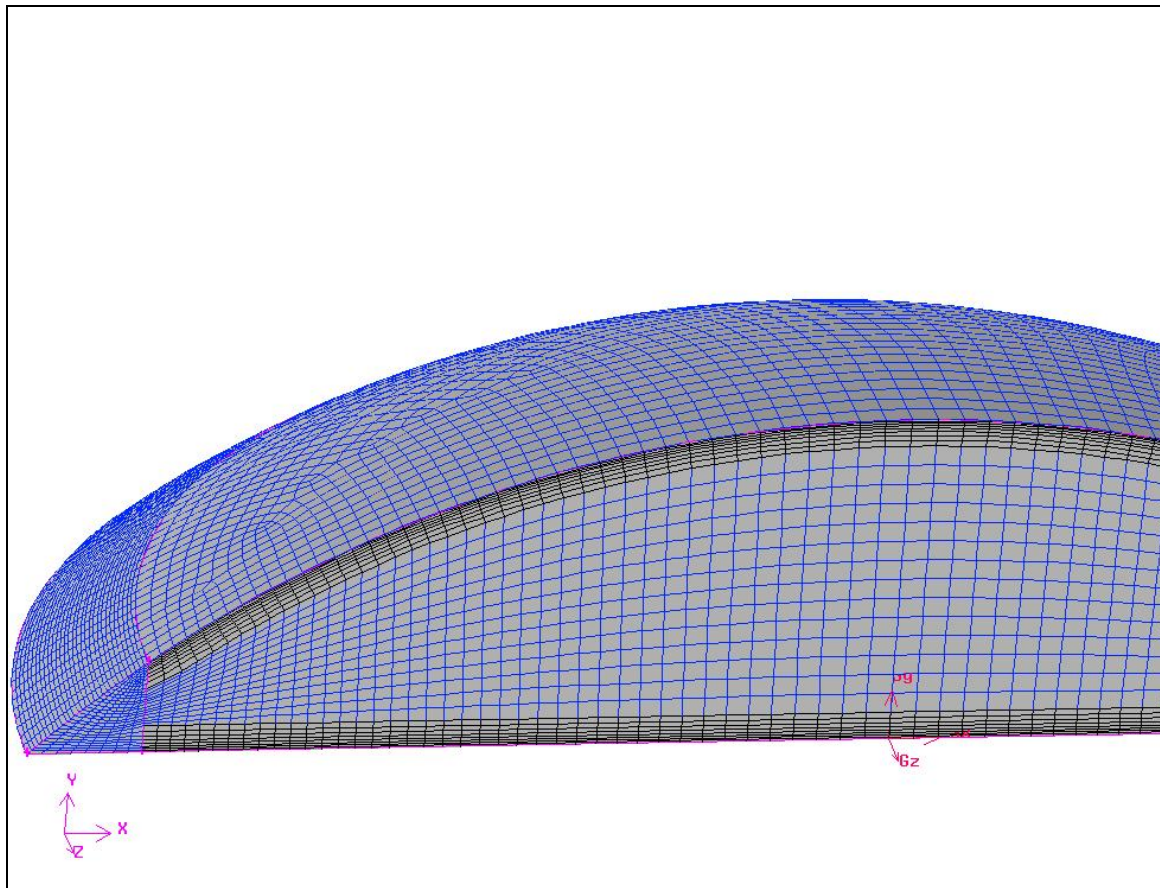


Figure 25. Numerical Mesh for the Type-B Domed Skylight Glazing Cavity.

4.5.2 Results and discussion

Predicted temperature and velocity fields in the cavity for the case of domed skylight glazing cavity Type-B ($\varnothing = 60$ cm, $H/\varnothing = 0.2$) in vertical position ($\theta = 90^\circ$) are shown in Figure 26 and for tilt angle ($\theta = 20^\circ$) are shown in Figure 27.

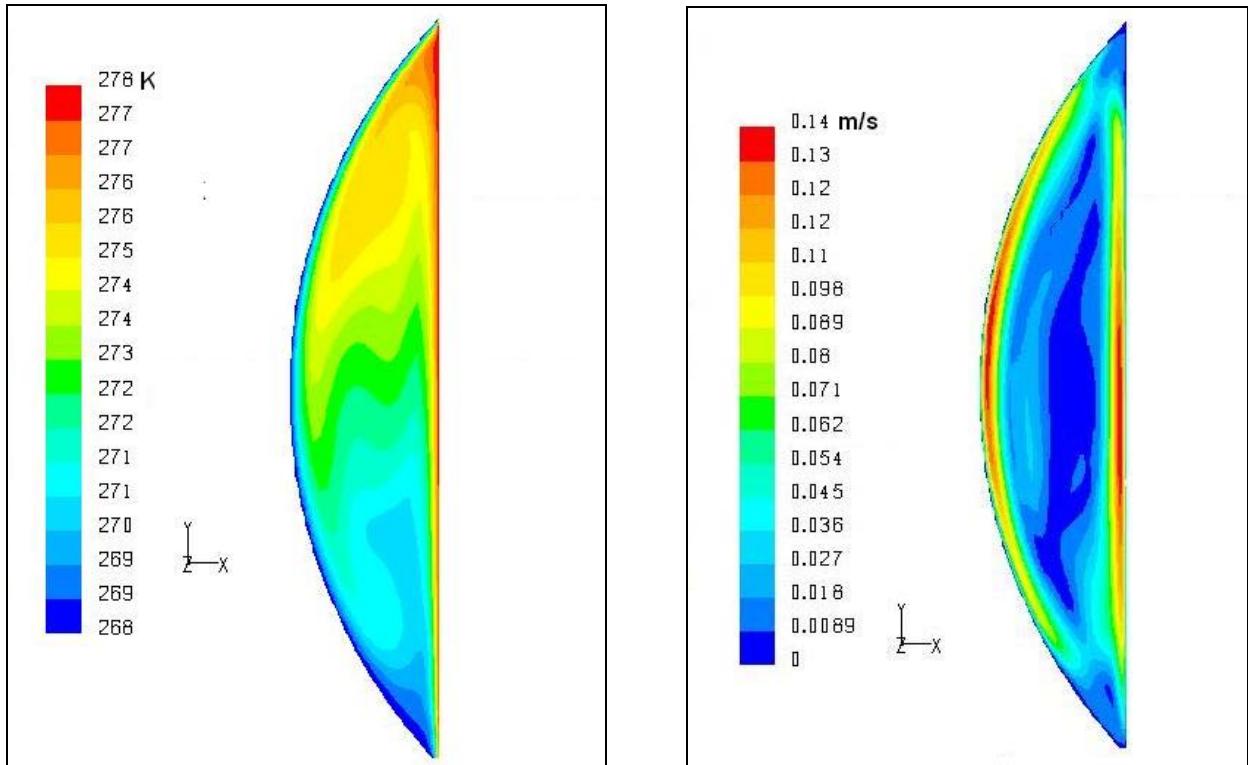


Figure 26. Temperature and Velocity Magnitude Distributions in a Symmetry Plane of the Type-B Domed Skylight Glazing Cavity at Vertical Orientation. $Ra = 23,000$ ($\Delta T = 10K$).

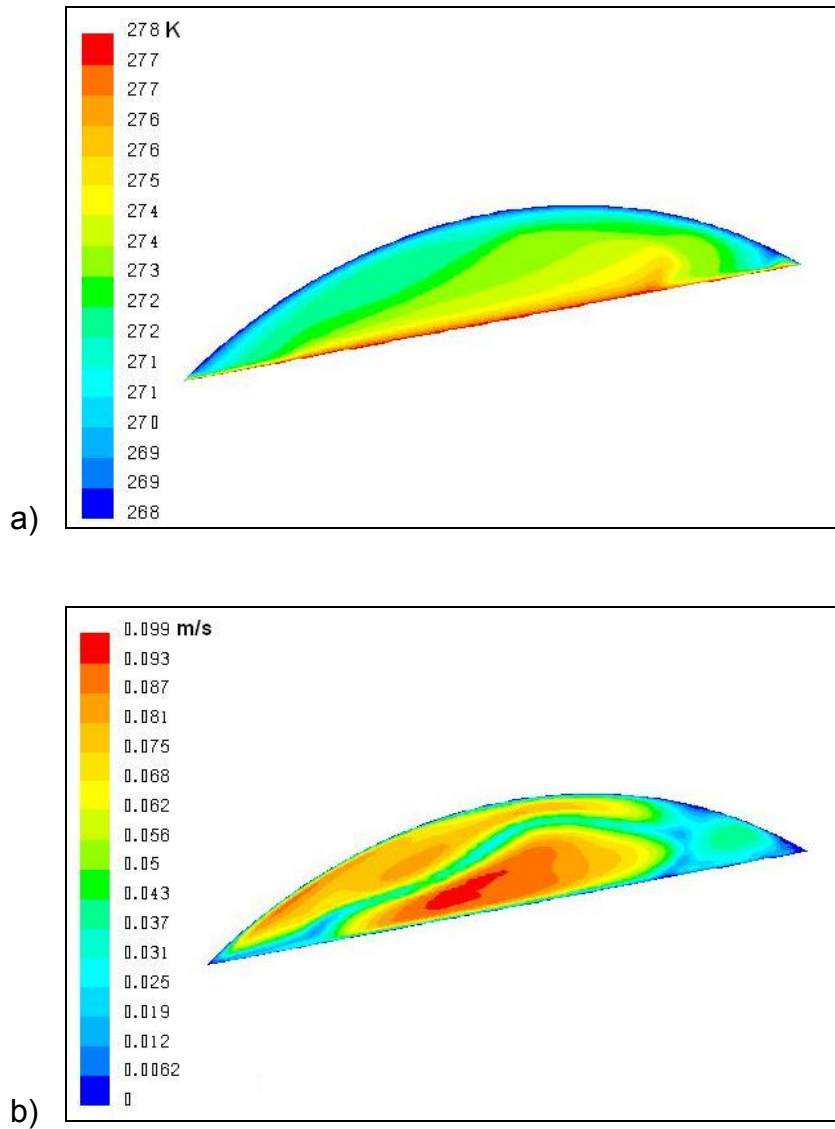


Figure 27. Temperature (a) and Velocity Magnitude (b) Distributions in a Symmetry Plane of the Type-B Domed Skylight Glazing Cavity at a tilt angle $\theta = 20^\circ$. $Ra = 23,000$ ($\Delta T = 10K$).

Simulation results are summarized in Table 6 in terms of thermal conductance (surface to surface heat transmission) in Type-B domed glazing cavity models for selected configurations and parameters.

Table 6. Thermal Conductance C_{cond} for the 3-D domed glazing cavity (Type-B).

| Glazing base diameter $\varnothing = 0.6$ m | | | Glazing base diameter $\varnothing = 1.2$ m | | |
|--|------------------------|------------------------|---|------------------------|------------------------|
| H/ $\varnothing = 0.1$ | H/ $\varnothing = 0.2$ | H/ $\varnothing = 0.3$ | H/ $\varnothing = 0.1$ | H/ $\varnothing = 0.2$ | H/ $\varnothing = 0.3$ |
| Cavity Thermal Conductance C_{cond} , W/(m ² K) | | | | | |
| 2.015 | 1.146 | 0.912 | 0.990 | 0.568 | 0.421 |

The following expression, derived from the present numerical study expresses heat flux q_{cond} due to conduction on inside cavity surface with errors less than 3% for most cases in comparing with numerical modeling of conduction heat transfer (Table 3) in domed glazing cavity

$$q_{cond} = \frac{\beta \cdot k \cdot \Delta T}{\frac{H}{2}} \quad (19)$$

Where:

β = Form-factor of dome glazing cavity heat transfer;

$$\beta = 2.0 + 4.9 \cdot \frac{H}{\varnothing}; \varnothing = 0.6\text{m} \quad (20)$$

$$\beta = 0.92 + 2.25 \cdot \frac{H}{\varnothing}; \varnothing = 1.2\text{m} \quad (21)$$

k = Air thermal conductivity at average temperature in the cavity;

ΔT = Temperature difference between cavity walls;

H = Height of the dome.

Using equation (20) the modified Nusselt number for the Type-B domed skylight glazing cavity can be expressed as:

$$Nu_m = \frac{q_{conv}}{\frac{2 \cdot \beta \cdot k \cdot \Delta T}{H}} \quad (22)$$

All heat transfer results are summarized in Table 7 and Figure 28 to Figure 31.

Table 7. Nusselt vs. Raleigh number Dependence for Type-B Domed Skylight Glazing Cavities

| Glazing base diameter $\varnothing = 0.6$ m | | | | | | | Glazing base diameter $\varnothing = 1.2$ m | | | | | |
|---|--|------|------------------------|------|------------------------|------|---|-------|------------------------|------|------------------------|------|
| H/ \varnothing | H/ $\varnothing = 0.1$ | | H/ $\varnothing = 0.2$ | | H/ $\varnothing = 0.3$ | | H/ $\varnothing = 0.1$ | | H/ $\varnothing = 0.2$ | | H/ $\varnothing = 0.3$ | |
| $\theta =$ | 90° | 20° | 90° | 20° | 90° | 20° | 90° | 20° | 90° | 20° | 90° | 20° |
| Ra | Nu number ($Nu = q_{conv} / q_{cond}$) | | | | | | | | | | | |
| 11300 | 1.247 | 1.3 | 1.76 | 1.81 | 2.18 | 2.28 | 1.677 | 1.786 | 2.55 | 2.67 | 3.45 | 3.76 |
| 22600 | 1.355 | 1.44 | 1.99 | 2.05 | 2.477 | 2.60 | 1.89 | 2.02 | 3.00 | 3.11 | 4.13 | 4.37 |
| 45200 | 1.48 | 1.6 | 2.28 | 2.22 | 2.84 | 2.91 | 2.177 | 2.33 | 3.49 | 3.52 | 4.89 | 5.18 |
| 67800 | 1.574 | 1.63 | 2.47 | 2.5 | 3.15 | 3.18 | 2.37 | 2.536 | 3.84 | 3.87 | 5.47 | 5.6 |

Modeling results in terms of modified Nu number, Nu_m are presented in Figure 28 for two glazing cavities (glazing base diameter $\varnothing = 0.6$ m and $\varnothing = 1.2$ m) with the same parameter $H/\varnothing = 0.2$ in vertical ($\theta = 90^\circ$) and tilted position ($\theta = 20^\circ$). From numerical results we can conclude that increasing base diameter of domed skylight glazing cavity from 0.6 m to 1.2 m results in increase of convection heat transfer by about 50% on average. This is true for vertical and tilted cavities. The intensity of convection heat transfer in tilted cavity under angle 20° differs by less than 4% when compared to the cavity in vertical position ($\theta = 90^\circ$) and that is why it can be considered as independent from tilt angle. It is also true for parameter $H/\varnothing = 0.3$.

However, in the case of parameter $H/\varnothing = 0.1$, the discrepancy of heat transfer intensity between two differently oriented cavities is about 8%. Comparison for the parameter $H/\varnothing = 0.1$ is shown in Figure 51.

Figure 30 shows heat transfer rate of domed skylight glazing cavities in vertical position ($\theta = 90^\circ$) with different parameter H/\varnothing (ratio of the dome height to the dome base diameter). The difference between predicted Nu for glazing cavities in vertical orientation ($\theta = 90^\circ$) for different H/\varnothing parameters is from 40% to 50%. Similar difference was observed in the case of tilted glazing cavities ($\theta = 20^\circ$) with different parameter H/\varnothing as shown in Figure 31.

For these reasons the heat transfer rate for these cases should be considered as dependent from parameter H/\varnothing .

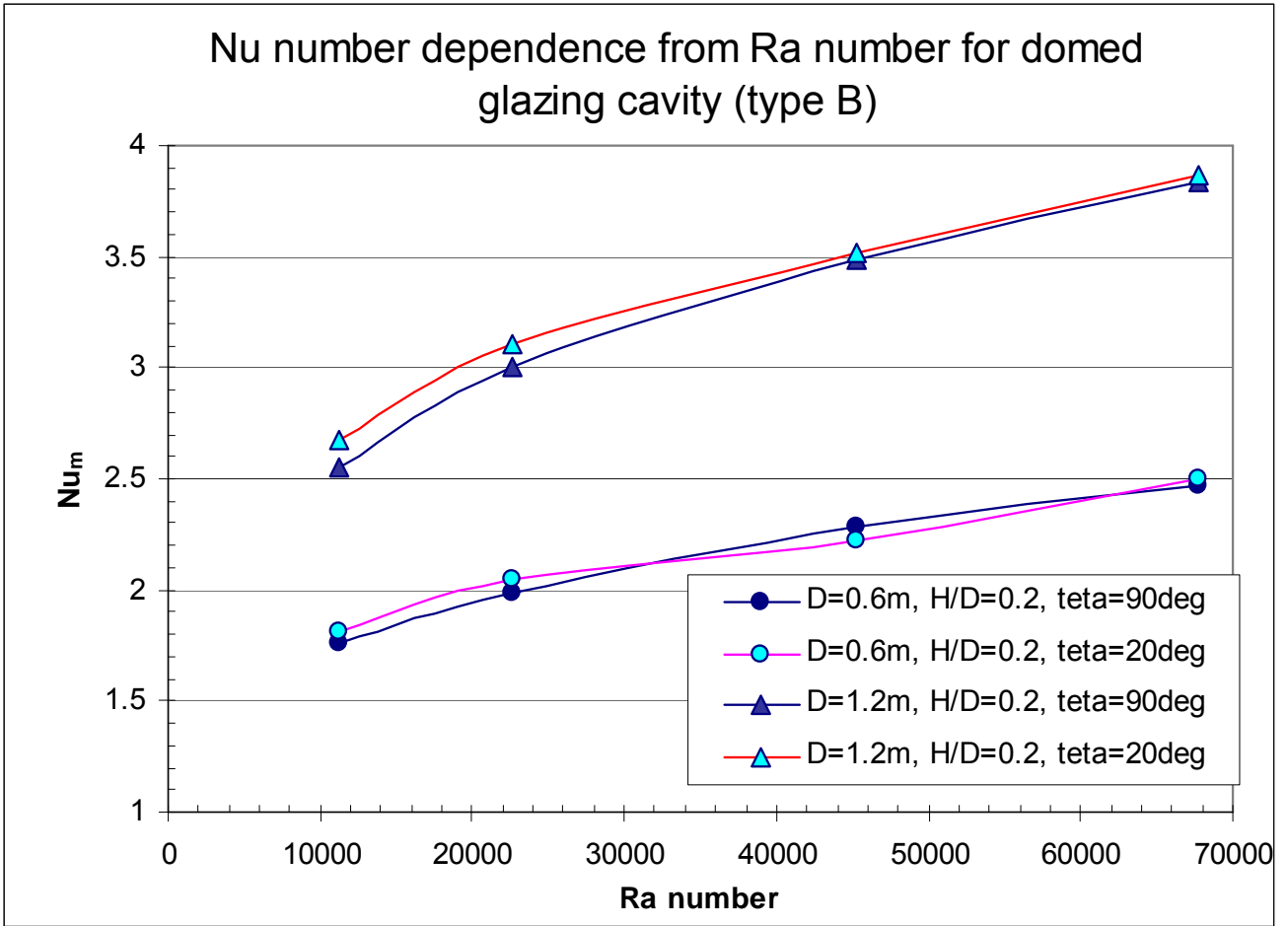


Figure 28. Comparison of Heat Transfer Rate for Type-B Domed Skylight Glazing Cavity with Base Diameters $\varnothing = 0.6$ m and $\varnothing = 1.2$ m. and $H/\varnothing = 0.2$

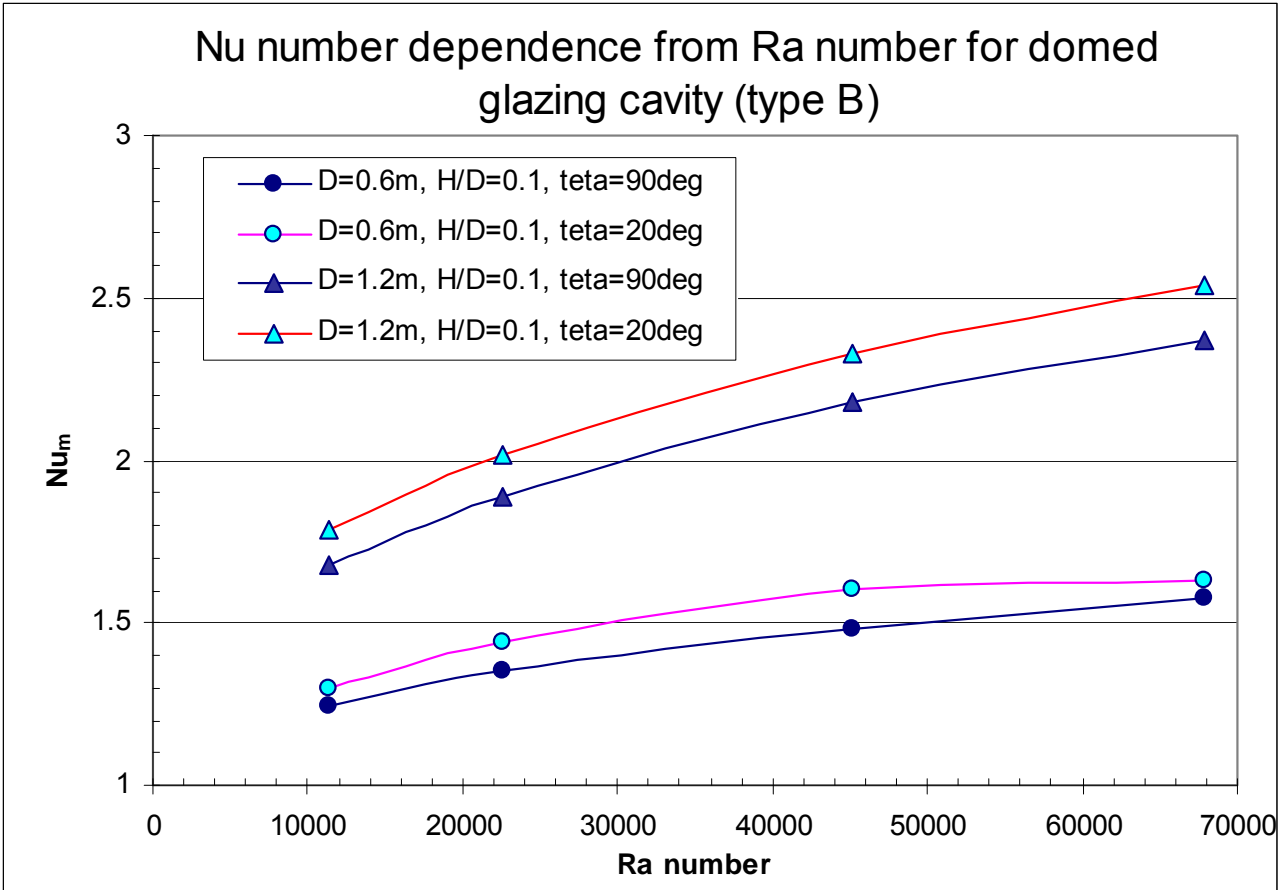


Figure 29. Comparison of Heat Transfer Rate for Type-B Domed Skylight Glazing Cavity with Base Diameters $\varnothing = 0.6$ m and $\varnothing = 1.2$ m. and $H/\varnothing = 0.1$.

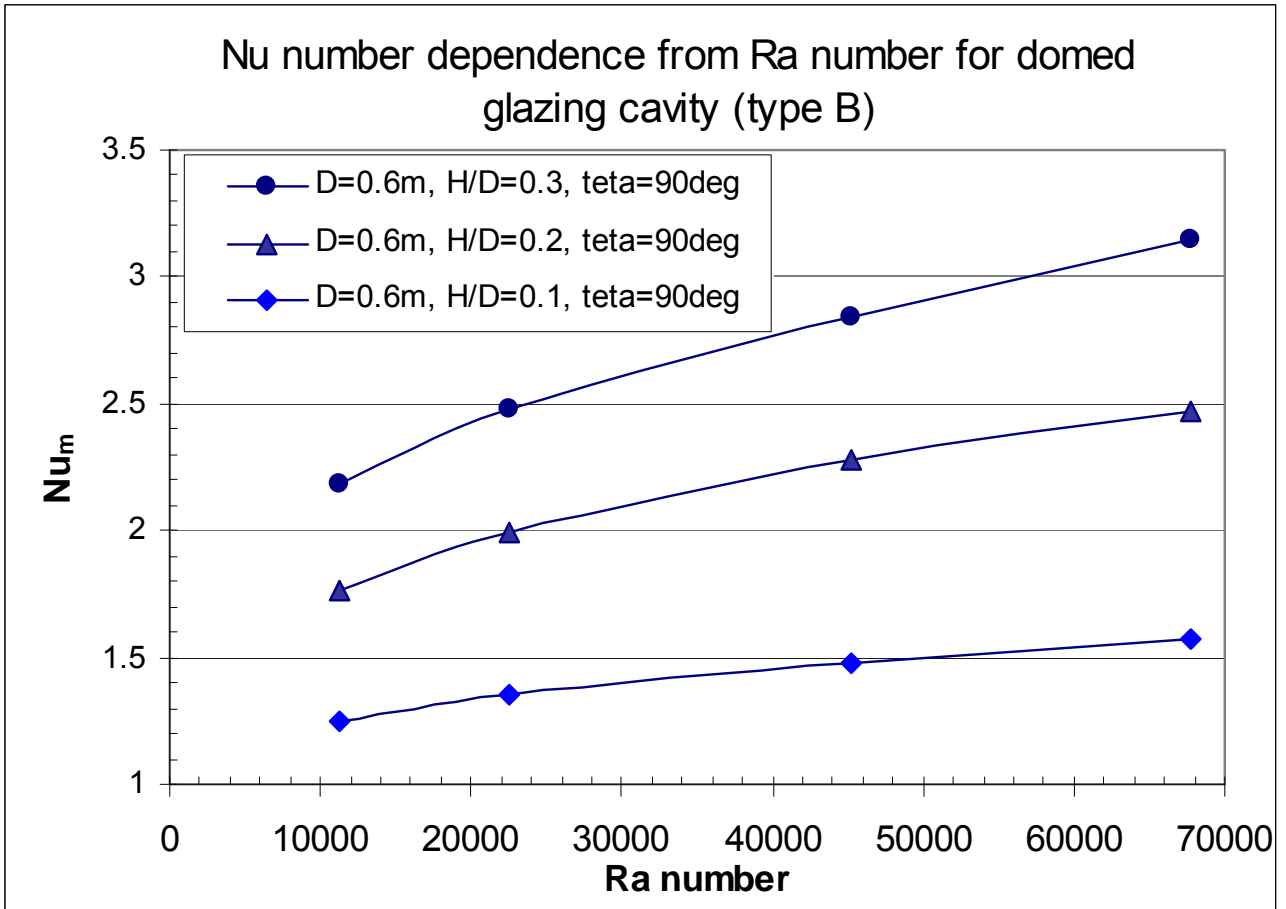


Figure 30. Heat transfer Rate Comparison for Type-B Domed Skylight Glazing Cavities in Vertical Orientation with Different Parameter H/\varnothing .

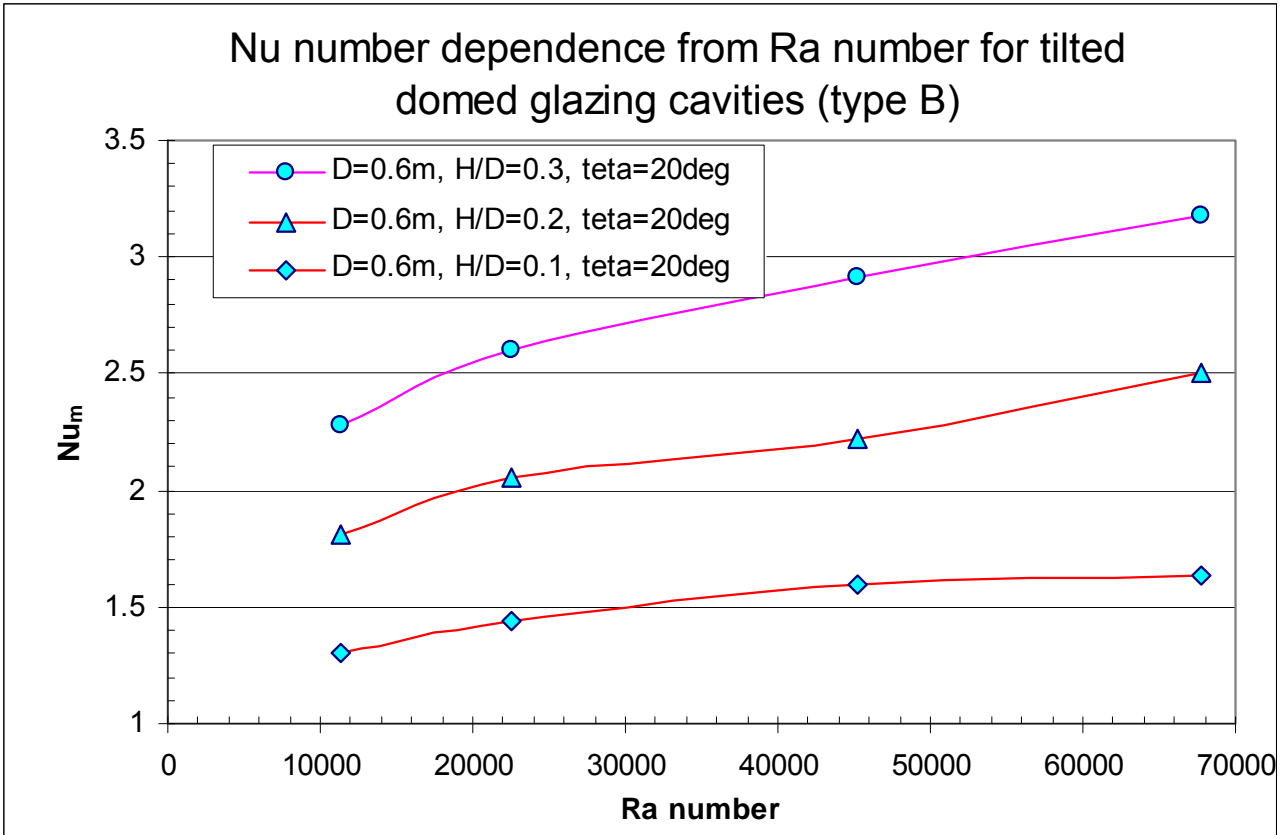


Figure 31. Heat transfer Rate Comparison for Type-B Domed Skylight Glazing Cavities in Tilted Orientation with Different Parameter H/\varnothing .

4.6 Heat transfer correlations for domed glazing cavity of a Type-B

4.6.1 Heat transfer correlations for Type-B domed skylight glazing cavities in vertical orientation

The following convection heat transfer correlations for Nu_m were derived from numerical modeling results for domed glazing cavities in vertical orientation ($\theta = 90^\circ$) as a function of Ra , H/\varnothing , and \varnothing :

a) Correlation for domed skylight glazing cavities with glazing base diameter $\varnothing = 0.6$ m:

$$Nu_{90} = -0.2 + (0.002 \cdot Ra)^{0.12}; \quad \frac{H}{\varnothing} = 0.1 \quad (23)$$

$$Nu_{90} = -0.1 + (0.002 \cdot Ra)^{0.19}; \quad \frac{H}{\varnothing} = 0.2 \quad (24)$$

$$Nu_{90} = 0.2 + (0.002 \cdot Ra)^{0.22}; \quad \frac{H}{\varnothing} = 0.3 \quad (25)$$

b) Correlation for domed glazing cavities with glazing base diameter $\varnothing = 1.2\text{m}$:

$$Nu_{90} = (0.002 \cdot Ra)^{0.17}; \quad \frac{H}{\varnothing} = 0.1 \quad (26)$$

$$Nu_{90} = 0.3 + (0.002 \cdot Ra)^{0.26}; \quad \frac{H}{\varnothing} = 0.2 \quad (27)$$

$$Nu_{90} = 0.8 + (0.002 \cdot Ra)^{0.31}; \quad \frac{H}{\varnothing} = 0.3 \quad (28)$$

Correlations (23) to (28) are used as endpoints in linear interpolation for determining modified Nu number for specified Ra number in the range of aspect ratio from $H/\varnothing = 0.1$ to $H/\varnothing = 0.3$ and glazing base diameter from $\varnothing = 0.6\text{ m}$ to $\varnothing = 1.2\text{ m}$. Figure 32 show how proposed correlations (23) to (25) are compare with numerical modeling results. Figure 33 show how proposed correlations (26) to (28) are compare with numerical modeling results. The maximum difference between correlations and modeling results is less than 2%.

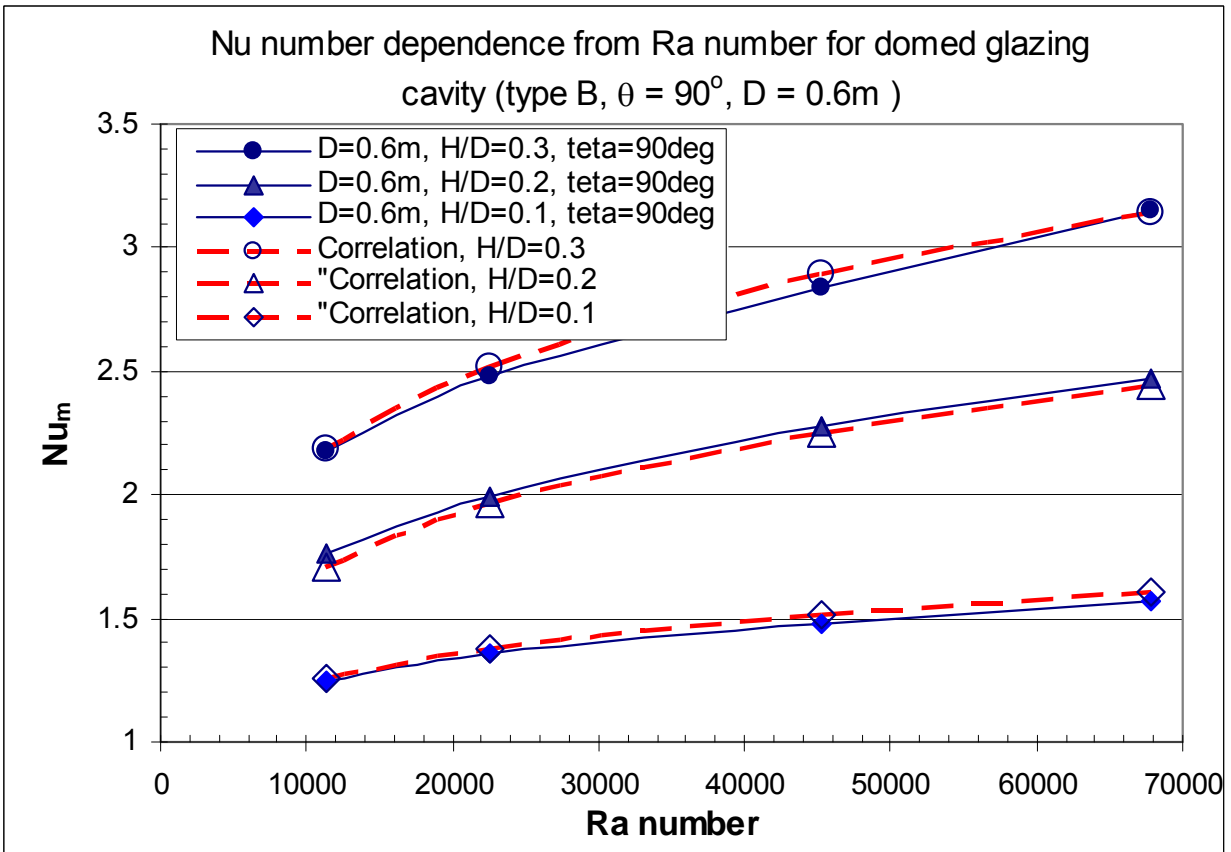


Figure 32. Comparison of Convective Heat Transfer Rates Predicted by Numerical Modeling and Correlations for Type-B Domed Glazing Cavity With Glazing Base Diameter $\varnothing = 0.6\text{ m}$.

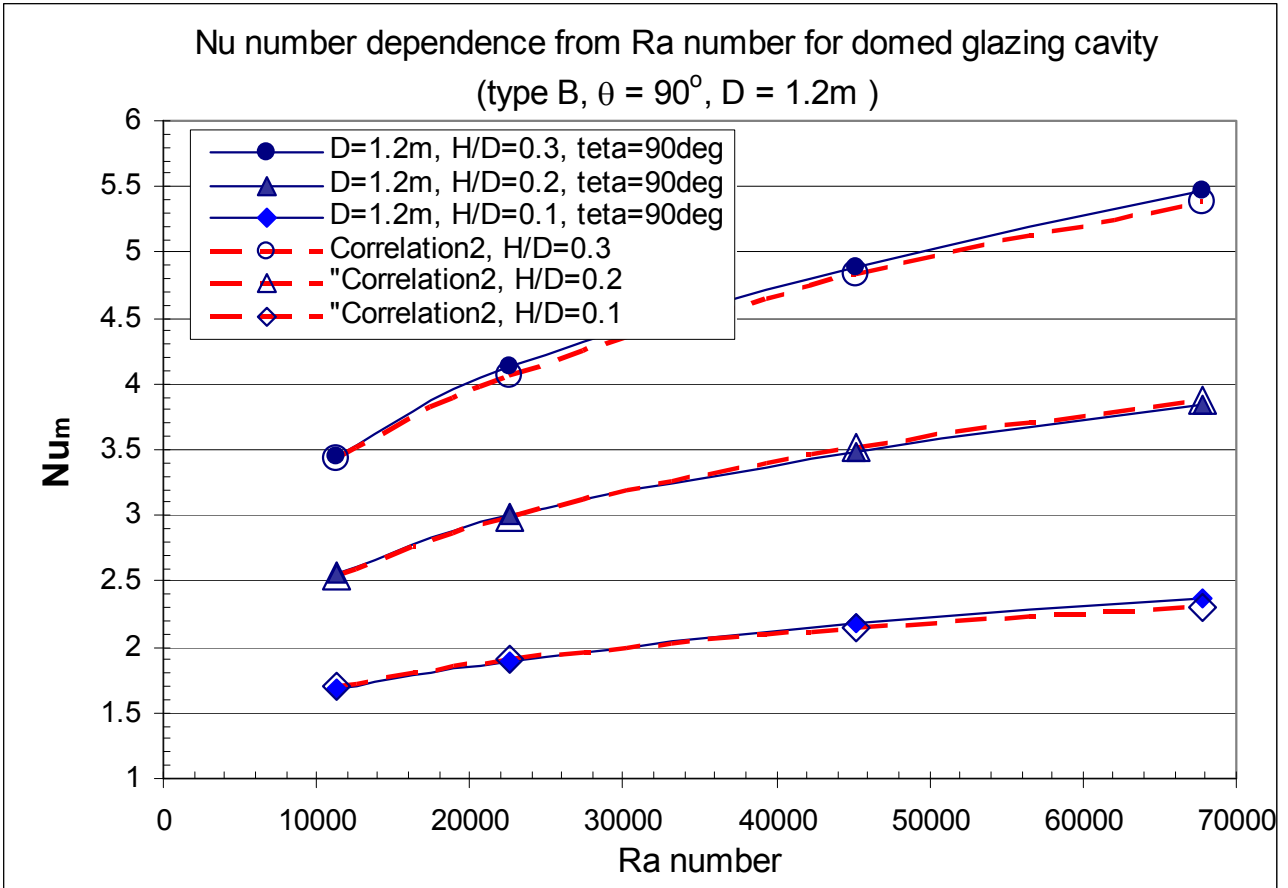


Figure 33. Comparison of Convective Heat Transfer Rates Predicted by Numerical Modeling and Correlations for Type-B Domed Glazing Cavity With Glazing Base Diameter $\varnothing = 1.2\text{ m}$.

Convective heat transfer coefficient is calculated from the Nu using the following relation:

$$h_c = Nu \frac{2 \cdot k}{d}$$

4.6.2 Heat transfer correlations for Type-B domed skylight glazing cavities in tilted orientation

The following convection heat transfer correlations for Nu_{20} were derived from numerical modeling results for domed skylight glazing cavities in titled orientation ($\theta = 20^\circ$) as a function of Ra , \varnothing , and H/\varnothing :

- a) Correlation for Type-B domed skylight glazing cavities with the glazing base diameter in the range of aspect ratio $H/\varnothing = 0.2$ to $H/\varnothing = 0.3$.

$$Nu_{20} = Nu_{90}; 0.2 \leq \frac{H}{\varnothing} \leq 0.3 \quad (29)$$

Where:

Nu_{90} = Nusselt number for the same glazing cavity in vertical orientation.

- b) Correlation for Type-B domed glazing cavities with the glazing base diameter aspect ratio $H/\varnothing = 0.1$:

$$Nu_{20} = -0.17 \cdot (0.002 \cdot Ra)^{0.12}; \varnothing = 0.6\text{m} \quad (30)$$

$$Nu_{20} = (0.002 \cdot Ra)^{0.19}; \varnothing = 1.2\text{m} \quad (31)$$

To calculate Nu for intermediate values of the glazing base diameter \varnothing and glazing base diameter aspect ratio H/\varnothing , linear interpolation between correlations (29) to (31) is used.

Figure 34 shows how proposed correlations (29) to (31) compare with numerical modeling results. The maximum difference between correlations and modeling results is less than 2%.

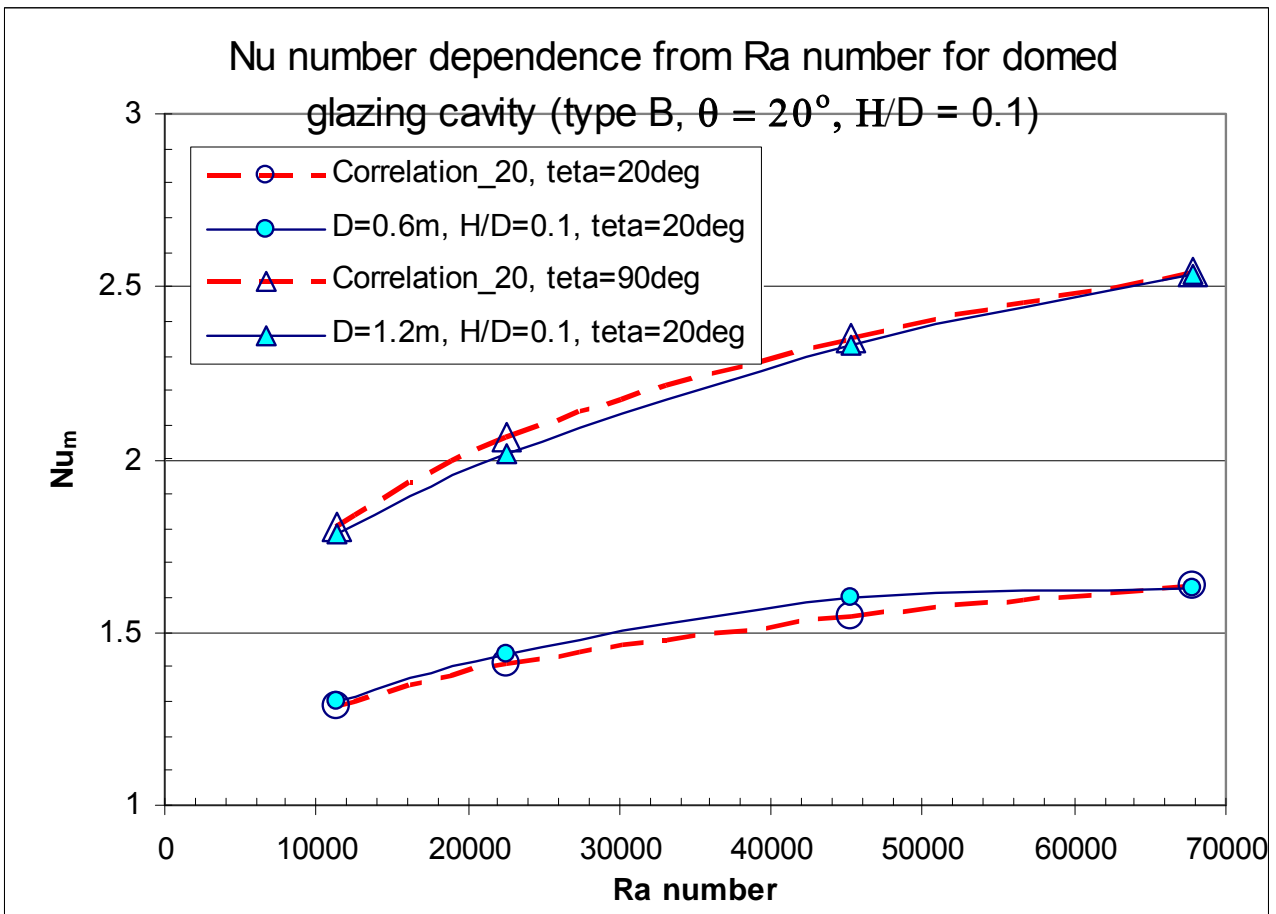


Figure 34. Comparison of Convective Heat Transfer Rates Predicted by Numerical Modeling and Correlations for Type-B Domed Glazing Cavity at Tilt angle $\theta=20^\circ$.

4.7 Summary

- 1) Domed skylight glazing cavities classification and formulas for creating 3-D numerical models of domed glazing cavities with non-uniform gap were developed. In particular, typical domed skylight glazing cavities can be categorized as Type-A, Type-B, or their combination (i.e., triple or quadruple glazed cavity).
- 2) Formulas for generating appropriate 3-D geometries using common geometry parameters, such as glazing base dimension, radius of curvature, and maximum gap width were developed.
- 3) The 3-D numerical models are developed for simulation of natural convection and detailed radiation heat transfer in domed skylight glazing cavities in vertical orientation (90° from horizontal) and tilted orientation (20° from horizontal).
- 4) The results of numerical modeling were expressed in terms of heat transfer rates and temperature distributions and presented in tabular and graph format.
- 5) Modified Nusselt number, Nu_m was developed to account for varying cavity gap widths.
- 6) Heat transfer correlations for domed skylight glazing cavities of a Type-A and Type-B were developed for vertical orientation ($\theta = 90^\circ$) and tilted orientation ($\theta = 20^\circ$).
- 7) Heat transfer for triple or quadruple dome skylight glazing cavities can be calculated using correlations for Type-A and Type-B cavities, by applying appropriate correlation to each cavity

5. EXPERIMENTAL STUDY AND VALIDATION OF HEAT TRANSFER IN DOMED SKYLIGHT GLAZING CAVITIES

This section presents results of experimental study of selected domed skylight glazing cavities, covering both Type A and Type B configurations. The goal of this study was to validate results of numerical 3-D modeling convection heat transfer in the vertical oriented domed skylight cavities against experiment results. The numerical modeling gives us information about temperature and heat flux distribution on glazing cavity walls that could be compared with test values under the same conditions. Thus, by verifying some of the numerical results, we are validating the subsequent correlations that are developed from these numerical results.

5.1 Experiment Description

Figure 35 shows a schematic drawing of the skylight glazing sample installation in insulation panel opening and locations of the attached heat flux meters and thermocouples.

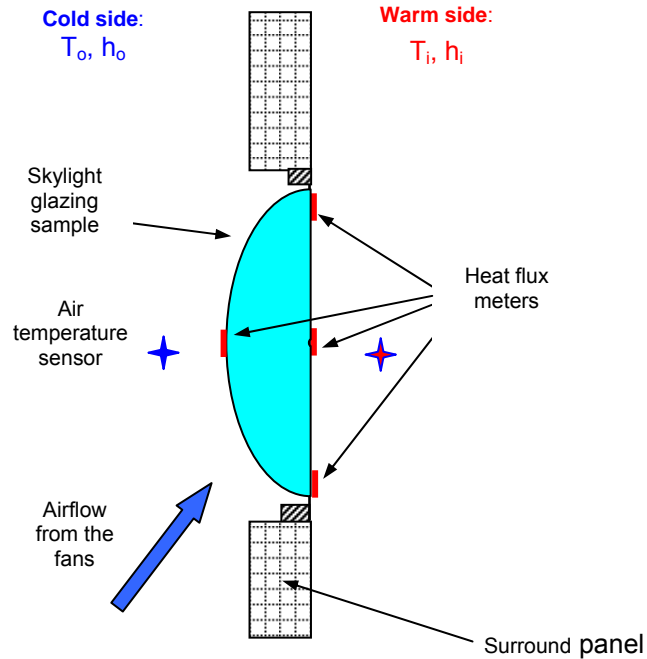


Figure 35. Schematic of Dome4d Skylight Glazing Sample Installation in the Surround Panel.

Test equipment

Experimental portion of the research work was done in a custom built measurement apparatus, consisting of the climatic chamber and measurement section. This measurement apparatus will be called Thermal Transmittance Apparatus.

Climatic chamber was constructed from the large size freezer, which was adapted and modified for this purpose. Inside dimensions of the freezer are $H \times W = 115\text{cm} \times 86\text{cm}$. The opening $114\text{cm} \times 85\text{cm}$ was cut in the freezer door and insulation panel consisting of polyisocyanurate board was installed in the opening. This climatic chamber is shown in Figure 36



Figure 36. Thermal Transmittance Apparatus with the Surround Panel and Specimen Opening in Place.

Thermal conductivity of the surround panel was measured using the LaserComp FOX 304 instrument (LaserComp 2003). This thermal conductivity was utilized in a calibration procedure for the Thermal Transmittance Apparatus. The FOX 304 instrument is calibrated using NIST SRM 1450b (Standard Reference Material of National Institute of Standards and Technology). Accuracy (total uncertainty) for the FOX 304 apparatus and measurement conditions is 1% (FOX304 instrument's specification).

Temperature sensors

The type-T thermocouples have been used for the temperature measurement. Six thermocouples were fabricated from gage 30 copper-constantan wires. The accuracy and quality of thermocouples were checked using Omega thermometer/calibrator (model CL23A) and the method of comparing with standard type-T thermocouple at three temperature points: -18C° , 0C° and 24C° .

Heat flux sensors

Four heat flux meters (transducers) have been used for the measurements of heat flux on domed skylight glazing surfaces. The heat flux meters of the integrating type with thickness of 2 mm were used. Two different sensor geometries were used; 1) Rectangular active measurement area with the overall sensor size of 40mm x 8mm; and 2) Circular active measurement area with the diameter of $\text{Ø} = 20\text{mm}$. The heat flux meters incorporate type-T thermocouples arranged in thermo par fashion.

From the calibration procedure, the total uncertainty of these heat flux meters was estimated as 4.9%.

Data Acquisition System

Agilent (model 34970A) Data Acquisition/Switch Unit was used for reading and storing temperature and electrical signals from thermocouples and heat flux meters.

Figure 37 shows skylight glazing sample installed in the surround panel opening, ready for testing.

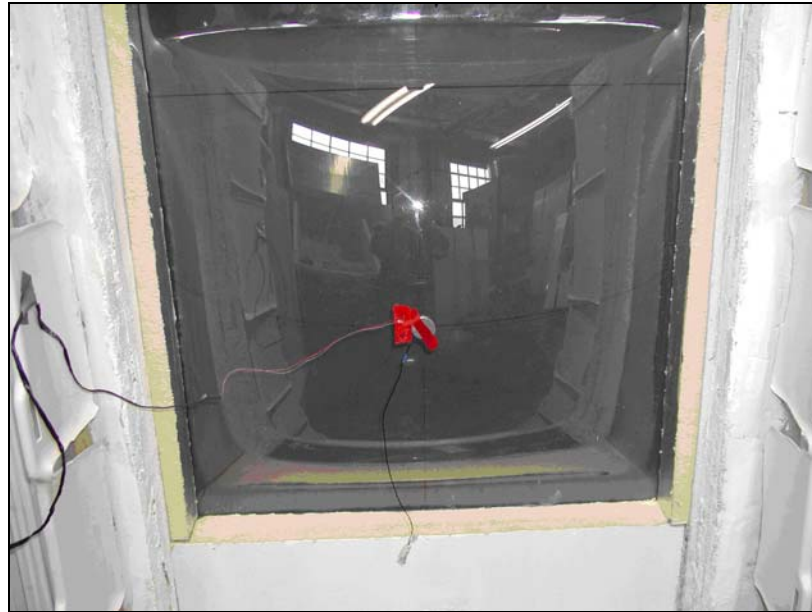


Figure 37. Domed Skylight Glazing Sample Installed in the Surround Panel Opening.

5.2 Calculation of the heat transfer (film) coefficient

The indoor and outdoor local surface heat transfer coefficients (also known as local film coefficients) h_i and h_o on glazing surfaces along the centerline were calculated from the following equation:

$$h_i = \frac{q_{HF_i}}{t_i - t_{si}} \quad (32)$$

$$h_o = \frac{q_{HF_o}}{t_o - t_{so}} \quad (33)$$

Where:

q_{HF_i} - heat flux measured by heat flux meter on indoor surface, W/m^2 ;

q_{HF_o} - heat flux measured by heat flux meter on outdoor surface, W/m^2 ;

- t_i - air temperature measured on indoor side, °C;
- t_o - air temperature measured on outdoor side, °C;
- t_{si} - surface temperature measured on indoor specimen surface, °C.
- t_{so} - surface temperature measured on outdoor specimen surface, °C.

5.3 Numerical model for Validation

In order to validate numerical model used for generating results for the full set of domed skylight configurations, selected fixed configuration is numerically modeled and experimentally tested and results compared. Local values of heat flux and surface temperatures are measured and compared to the equivalent values in a numerical model. The boundary conditions applied to the numerical model are based on the values obtained during the measurement (see Section 5.2).

5.4 Domed Skylight Glazing Type-A

Type-A glazing for domed skylights has two curved walls. Figure 38 and Figure 39 depict the Type-A test sample, prepared for thermal testing. The convex-concave glazing is fabricated from two 2.5 mm sheets of acrylic (polymethylmetacrilate) with the maximum gap thickness of 25 mm. The height of the glazing is 16 cm. The base of the sample has the size 56 cm x 56 cm (22"x22"). Figure 40 shows a schematic representation of the domed skylight glazing sample installation in surround panel opening and locations of the attached heat flux meters and thermocouples.



Figure 38. Test Sample for the Type-A Domed Skylight Glazing.

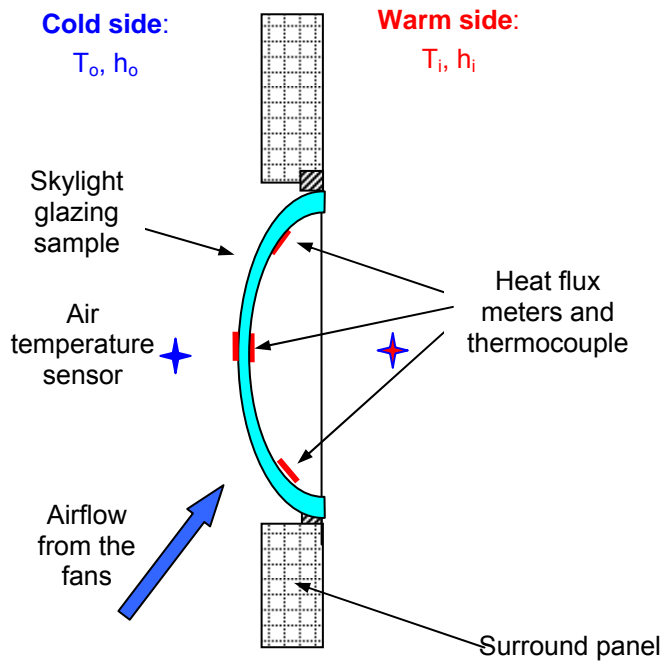


Figure 39. Schematic of the Domed Skylight Glazing Installation in a Surround Panel.

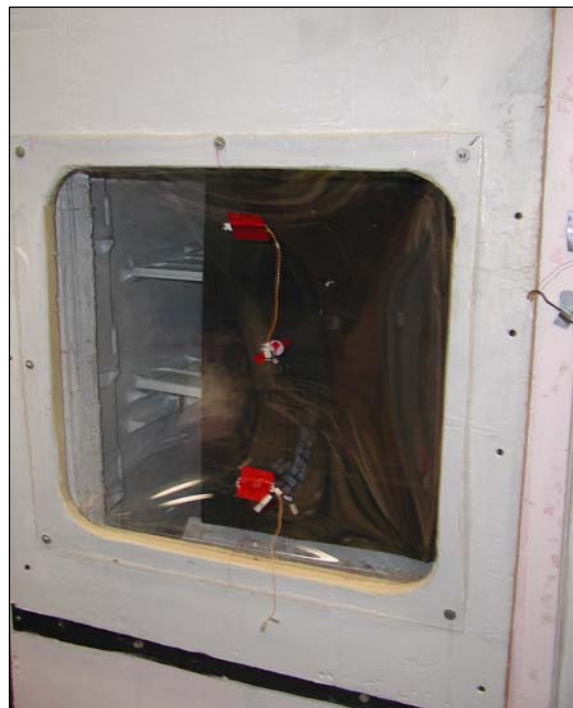


Figure 40. Schematic of the Type-A Domed Skylight Glazing Sample Installation in the Surround Panel.

Description of boundary conditions and numerical model.

Figure 41 and Figure 42 show boundary conditions and geometry of the 3-D Type-A domed glazing cavity numerical model. The model was created using geometrical parameters for the dome glazing cavity sample that was measured in a thermal transmittance apparatus. The following dimensions were used: base diameter $\varnothing = 0.56$ m, ratio of glazing height to the base diameter $H/\varnothing = 0.28$ and gap width 25 mm. Temperatures t_h and t_c were recorded during an experiment and applied to the numerical model. Surface heat transfer coefficients h_h and h_c were calculated using equations in Section 5.2.

For the simulation of convection heat transfer in a domed glazing cavity a laminar viscous model with Boussinesq approximation was used. Thermo-physical properties of air were treated as constants and were evaluated at the temperature of 0°C using standard gas correlations (ISO 2003). Radiation heat transfer was modeled using Fluent DTRM radiation model. Emissivity of surfaces participating in a heat transfer (domed glazing cavity surfaces facing the cavity) were defined as $\varepsilon = 0.9$.

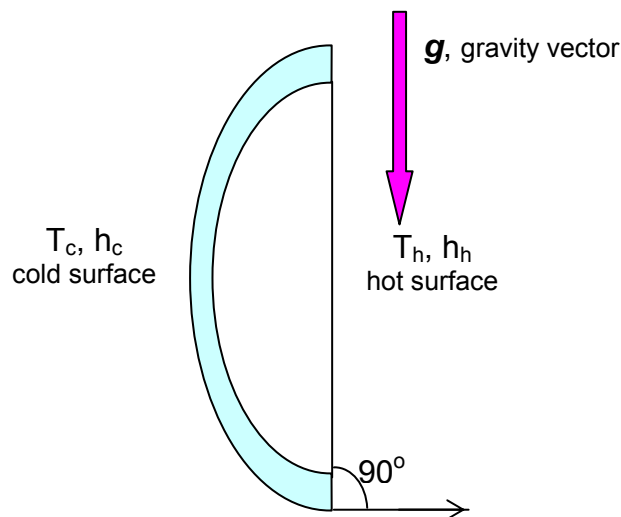


Figure 41. Boundary Conditions and Configuration for the Type-A Domed Skylight Glazing Cavity Numerical Model in Vertical Position.

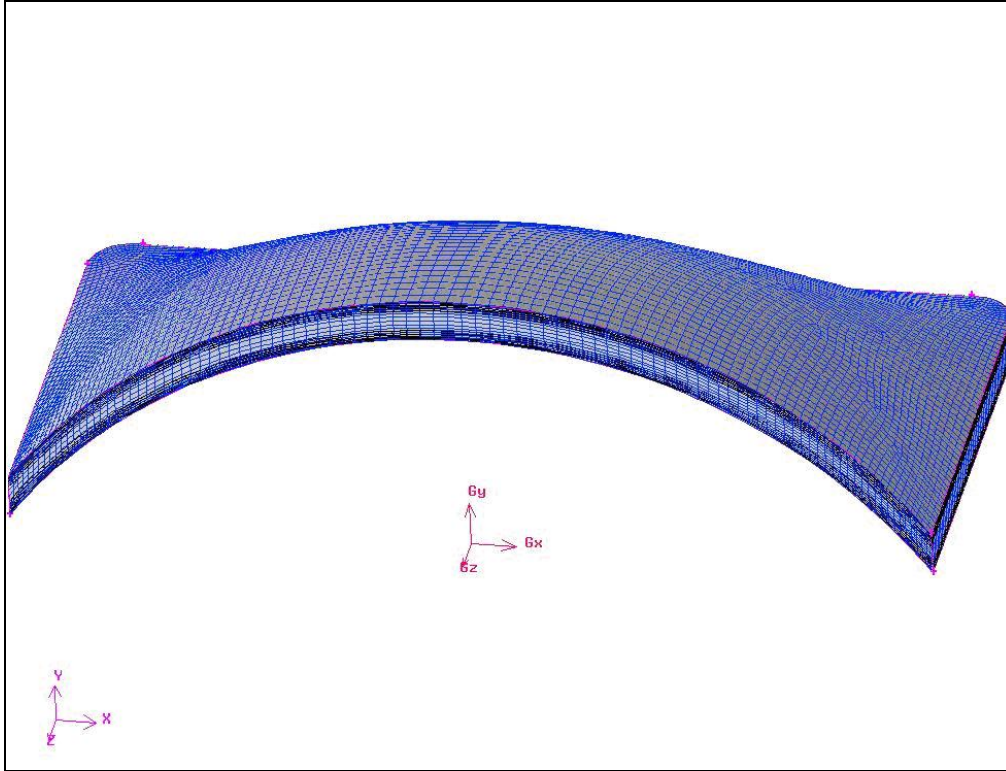


Figure 42. Finite Volume Mesh for the Type-A Domed Skylight Glazing Cavity ($\varnothing = 0.56$ m, $H/\varnothing = 0.28$, gap $d = 25$ mm).

Simulation Results and Comparison to the Experimental Results:

Results of numerical model include detailed heat flux, temperature and velocity fields for every region of the model. Figure 43 shows temperature and velocity fields in the vertical Type-A domed skylight glazing cavity.

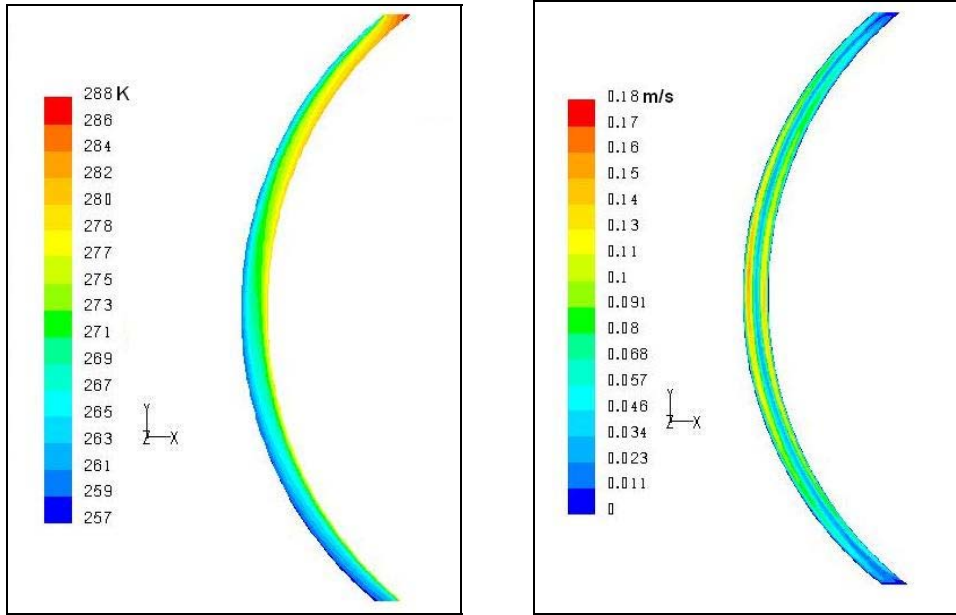


Figure 43. Predicted Temperature and Velocity Magnitude Distributions in a Symmetry Plane of a Type-A Domed Skylight Glazing Cavity.

Heat flux and temperature results for the predetermined locations, coinciding with the measurement locations, are presented in Table 8 and in Figure 44. These results are compared with the results of experimental measurements. Comparison of results shows that 3-D numerical model makes good prediction of the heat flow magnitudes and temperatures. The difference between measured and predicted average heat fluxes is within 3% for the most of the glazing surface and only in the bottom part the difference is 7%. The maximum difference in surface temperatures in the central area of glazing is 0.5 °C, which is excellent.

Table 8. The comparison Between Experimental and Numerical Results for the Domed Skylight Glazing, Type-A

| Method | Boundary conditions: T, °C; h, W/(m ² K) | | | | Hot wall surface temperature T _h , °C | Heat flux on hot wall, W/m ² | | |
|---------------|--|-----|-------|------|--|--|-------|-------|
| | T | h | T | h | | Location (Fig. 7) | | |
| | | | | | | 1 | 2 | 3 |
| Test | 20.8 | 8.3 | -19.0 | 22.0 | 8.1 | 128.6 | 107.6 | 107.9 |
| Simulation | 20.8 | 8.3 | -19.0 | 22.0 | 7.6 | 129.5 | 115.7 | 100.7 |
| Difference, % | | | | | | -0.7 | -7.0 | +6.7 |

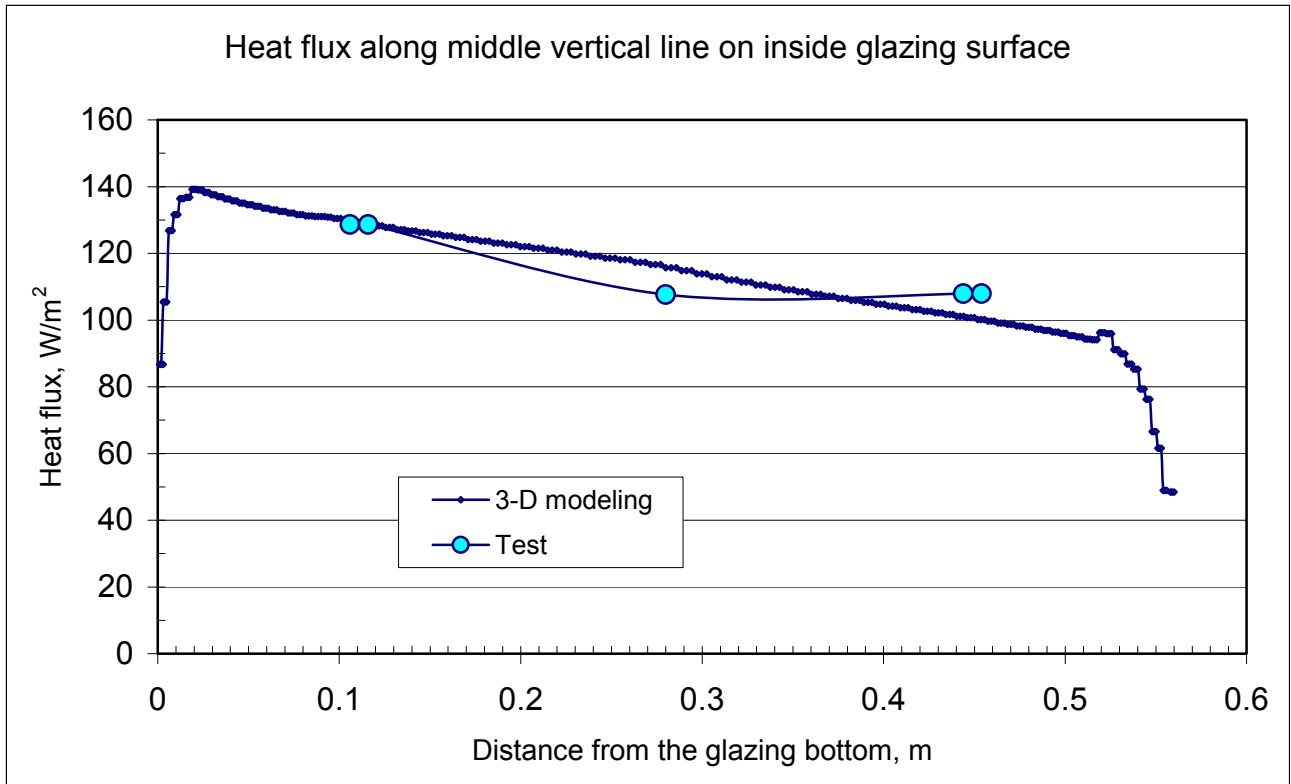


Figure 44. Comparison of Heat Flux Distribution Along the Vertical Symmetry Line on the Warm Glazing Surface of the Type-A Domed Skylight Glazing

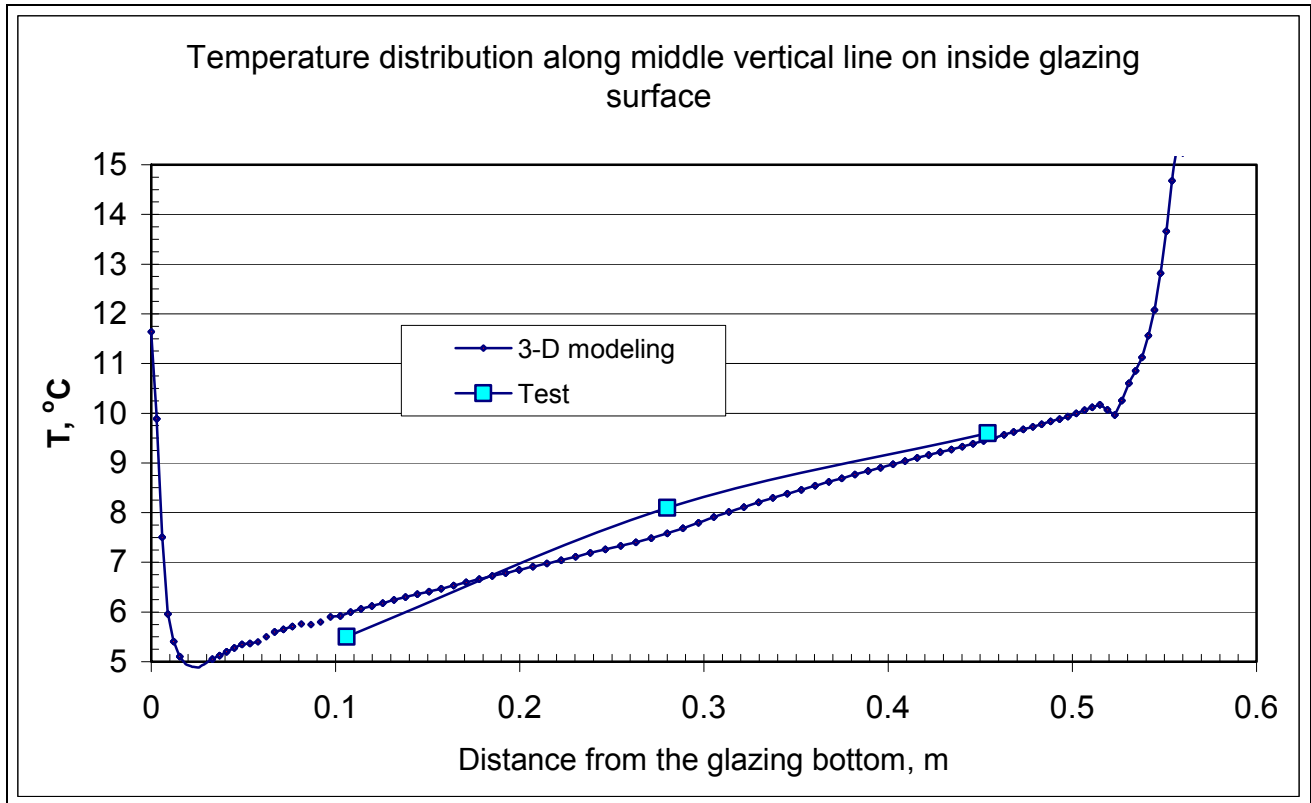


Figure 45. Comparison of Temperature Distribution Along the Vertical Symmetry Line on the Warm Glazing Surface of the Type-A Domed Skylight Glazing

Effect of the Surface Heat Transfer Coefficient Magnitude on the Warm Surface

To estimate range and dependence of indoor surface heat transfer coefficient on curved glazing surface temperature facing indoors, two measurements were done using different temperature differential. Heat fluxes and surface temperatures were measured in three locations under steady state conditions for two temperature differences $\Delta = T_h - T_c = 39.8^\circ\text{C}$ and $\Delta = 37.7^\circ\text{C}$. Results are presented in Figure 46.

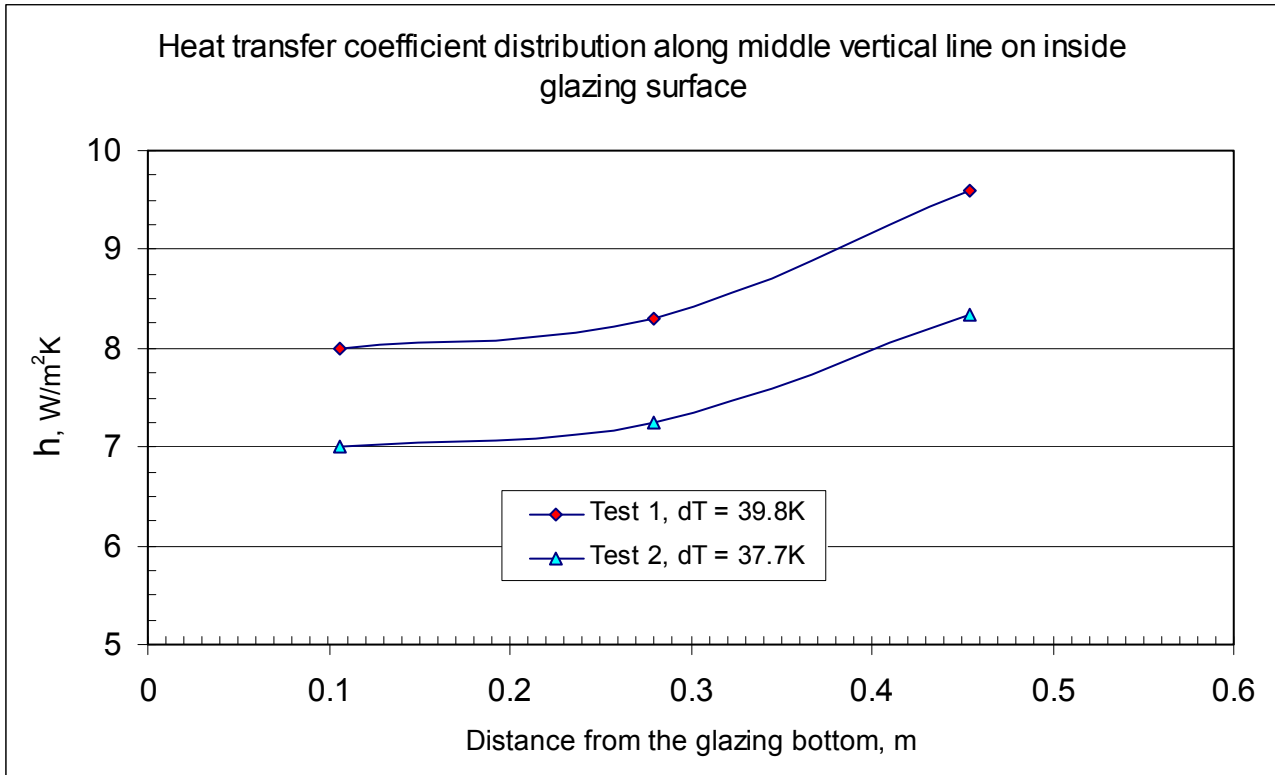


Figure 46. Heat Transfer Coefficient Distribution on the Warm Glazing Surface of the Type-A Domed Skylight Glazing

5.5 Domed Skylight Glazing Type-B

Type B glazing for domed skylights has one curved wall and other flat wall (flat wall oriented towards indoor side). Figure 47 depicts the type B test sample, prepared for thermal testing. The convex glazing is fabricated from 2.5 mm sheet of acrylic (polymethylmetacrilate) sheet. The maximum gap and the height of the glazing is 13.5 cm. The base of the sample has the size 56 cm x 56 cm (22"x22"). For testing purposes the convex acrylic sheet was attached to flat rigid PVC 3.2 mm sheet that plays the role of the second glazing layer in the experiment.



Figure 47. Test Sample for the Type-B Domed Skylight Glazing.

Description of boundary conditions and numerical model.

Figure 48 and Figure 49 show boundary conditions and geometry of the 3-D Type B domed glazing cavity numerical model. The model was created using geometrical parameters for the dome glazing cavity sample that was measured in a Heat Transmittance apparatus. The following dimensions were used: base diameter $\varnothing = 0.56$ m, ratio of glazing height to the base diameter $H/\varnothing = 0.24$. temperatures t_h and t_c were recorded during an experiment and applied to the numerical model. Surface heat transfer coefficients h_h and h_c were calculated using equations in Section 5.2.

For the simulation of convection heat transfer in a domed glazing cavity a laminar viscous model with Boussinesq approximation was used. Thermo-physical properties of air were treated as constants and were evaluated at the temperature of 0°C using standard gas correlations (ISO 2003). Radiation heat transfer was modeled using Fluent DTRM radiation model. Emissivity of surfaces participating in heat transfer (domed glazing cavity surfaces facing the cavity) were defined as $\varepsilon = 0.9$.

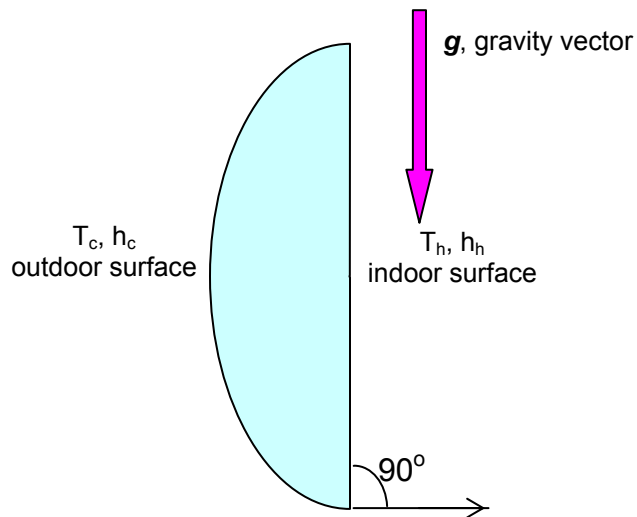


Figure 48. Boundary Conditions and Configuration for the Type-B Domed Skylight Glazing Cavity Numerical Model in Vertical Position.

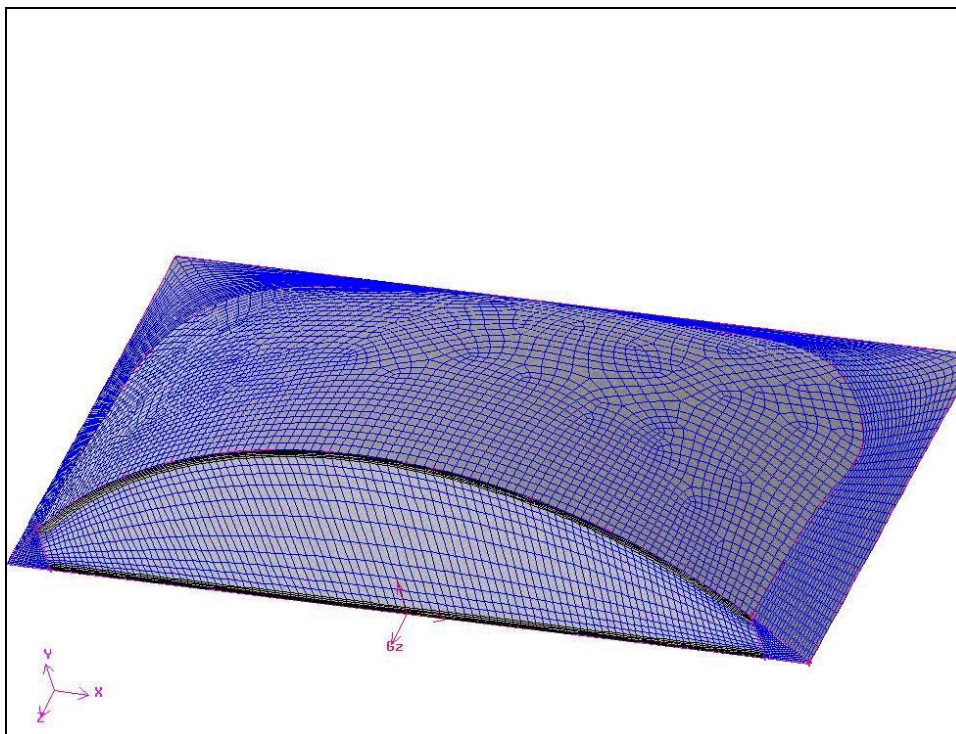


Figure 49. Finite Volume Mesh for the Type-B Domed Skylight Glazing Cavity ($\varnothing=0.56$ m, $H/\varnothing=0.24$).

Simulation Results and Comparison to the Experimental Results:

Results of the numerical model include detailed heat flux, temperature and velocity fields for every region of the model. Figure 50 shows temperature and velocity fields in the vertical domed skylight glazing cavity.

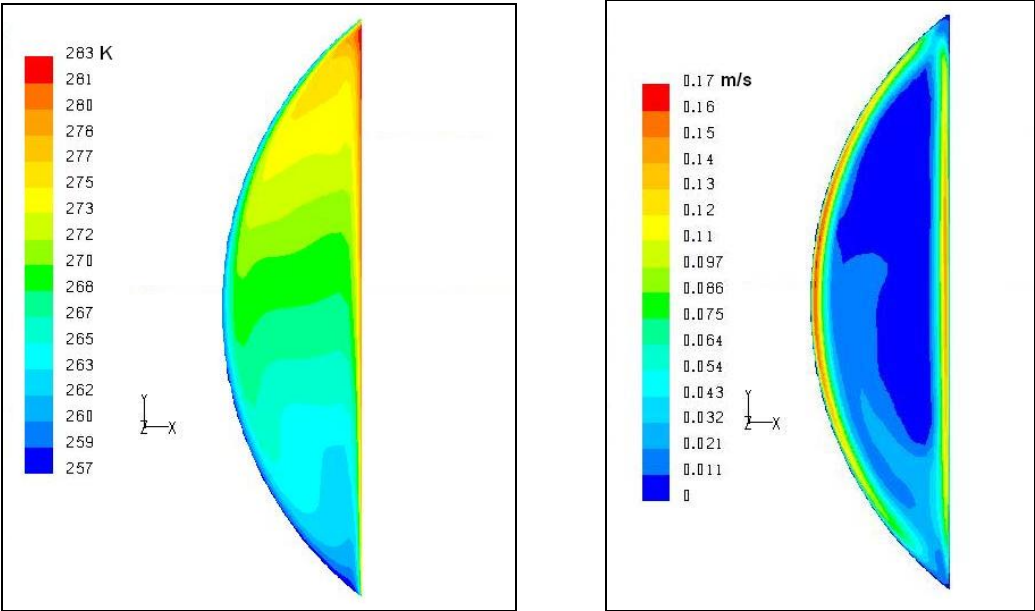


Figure 50. Predicted Temperature and Velocity Magnitude Distributions in a Symmetry Plane of a Domed Glazing Cavity.

Heat flux and temperature results for the predetermined locations, coinciding with the measurement locations, are presented in Table 9 and in Figure 51. These results are compared with the results of experimental measurements. Comparison of results shows that 3-D numerical model makes good prediction of the heat flow magnitudes and temperatures. The difference between measured and predicted average heat fluxes is within 3% for the most of the glazing surface and only in the bottom part the difference is 7.2%. The difference in surface temperatures in the central area of glazing is 1.5 °C, which is also very close.

Table 9. The comparison Between Experimental and Numerical Results for the Domed Skylight Glazing, Type-B

| Source of Data | Boundary conditions: T, °C; h, W/(m ² K) | | | | Hot wall surface temperature T _h , °C | Heat flux on hot wall, W/m ² | | |
|----------------|--|------|-------|------|--|--|-------|-------|
| | T | h | T | h | | Location (Fig. 7) | | |
| | | | | | | 1 | 2 | 3 |
| Test | 22.2 | 11.1 | -18.6 | 21.3 | 11.0 | 166.3 | 125.5 | 109.2 |
| Simulation | 22.2 | 11.1 | -18.6 | 21.3 | 9.5 | 154.2 | 128.2 | 111.8 |
| Difference, % | 0.0 | | 0.0 | | | +7.2 | -3.0 | -2.4 |

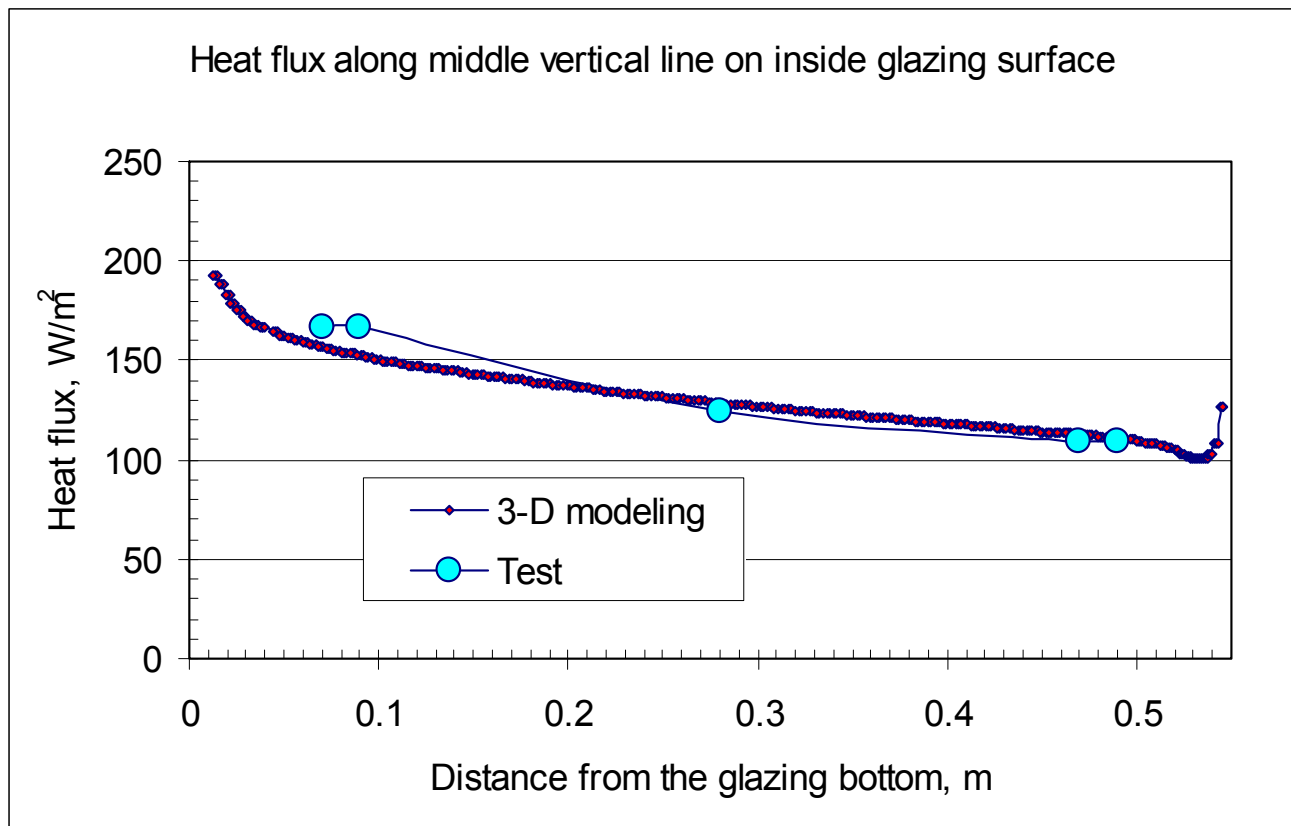


Figure 51. Comparison of Heat Flux Distribution Along the Vertical Symmetry Line on the Warm Glazing Surface of the Domed Skylight Glazing Type-B.

5.5 Summary

- 1) Experimental validation of numerical modeling for domed skylight glazing cavities using Thermal Transmittance Apparatus was developed for this research project.

This experimental validation can lead to the development of the alternative experimental technique for measuring and validating numerical modeling of heat transfer in fenestration products,

- 2) Measurements were done on Type-A and Type-B domed skylight glazing cavities for the purpose of validating numerical model. One sample (type B with one convex and other flat glass sheet) has base size 56 cm x 56 cm (22"x22") and height 13.5 cm; Second sample (type A with one convex and other concave glass sheet and with gap between them 25 mm) has base size 56 cm x 56 cm (22"x22") and height 16 cm.
- 3) The distribution of heat transfer coefficient on curved warm (indoor) glazing surface was obtained from test results for two different air to surface temperature differences.
- 4) Results of measuring heat flux through the warm wall of the domed skylight glazing and surface temperature were compared with 3-D numerical simulation results under the same boundary conditions. From the comparison it can be concluded that 3-D numerical model predicts well heat fluxes and surface temperatures on the glazing surface. Average difference in predicted and measured average heat fluxes is within 5% and maximum difference is 7.2% and average temperature difference is within 0.5°C at maximum difference of 1.5°C.
- 5) 3-D numerical model can be used with confidence to generate full set of results for all configurations and to generate heat transfer correlations.

6. CONCLUSIONS

1. Measurements of heat flux rates using surface heat flux transducers can be used to validate numerical modeling of complex convection and radiation heat transfer models and can lead to the development of a measurement standard for these kind of measurements,
2. Experimental validation of numerical modeling for all types of domed skylight glazing cavities produced very good to excellent agreement and gives high degree of confidence in the numerical modeling results,
3. 3-D numerical models of convection and radiation heat transfer in domed skylight glazing cavities were required to capture fluid flow details in domed skylight glazing cavities and to provide adequate accuracy of numerical modeling,
4. Domed skylight glazing cavities were categorized in three distinct groups, labeled Type-A, Type-B, and Type-C. Type-C, consisting of three glazing layers, can be constructed by combining Type-A and Type-B, so its heat transfer rates can be calculated by combining Type-A and/or Type-B cavities and applying appropriate correlations for these cavities.
5. Heat transfer correlations for calculating convective heat transfer rates in domed skylight glazing cavities were developed for Type-A and Type-B cavities for all relevant geometric parameters.

7. RECOMMENDATIONS

1. New heat transfer correlations for all types of domed skylight glazing cavities are proposed to be used for computer modeling of domed skylights and presented below:

| Glazing Cavity | Tilt angle | Correlation |
|---|---------------------|---|
| Type-A | $\theta = 90^\circ$ | $Nu_{90} = 0.95 \cdot \left(0.01 \cdot Ra \cdot \frac{d}{\emptyset}\right)^{0.08}$; $d \leq 0.05$ m |
| | | $Nu_{90} = 0.95 \cdot (0.00125 \cdot Ra)^{0.12}$; $d = 0.075$ m and $\emptyset \leq 0.6$ m |
| | | $Nu_{90} = 0.95 \cdot (0.000625 \cdot Ra)^{0.13}$; $d = 0.075$ m and $\emptyset = 1.2$ m |
| | | Linear interpolation for d and \emptyset in-between above values |
| | $\theta = 20^\circ$ | $Nu_{20} = Nu_{90} \cdot \left[1.03 + 2.3 \cdot 10^{-5} \cdot Ra \cdot \left(\log_{10}\left(\frac{H}{\emptyset}\right) + 0.7\right)^2\right]$; $d \leq 0.075$ m; $\emptyset \leq 1.2$ m; $H/\emptyset \leq 0.3$ |
| Type-B | $\theta = 90^\circ$ | $Nu_{90} = -0.2 + (0.002 \cdot Ra)^{0.12}$; $\frac{H}{\emptyset} = 0.1$ and $\emptyset = 0.6$ m |
| | | $Nu_{90} = -0.1 + (0.002 \cdot Ra)^{0.19}$; $\frac{H}{\emptyset} = 0.2$ and $\emptyset = 0.6$ m |
| | | $Nu_{90} = 0.2 + (0.002 \cdot Ra)^{0.22}$; $\frac{H}{\emptyset} = 0.3$ and $\emptyset = 0.6$ m |
| | | $Nu_{90} = (0.002 \cdot Ra)^{0.17}$; $\frac{H}{\emptyset} = 0.1$ and $\emptyset = 1.2$ m |
| | | $Nu_{90} = 0.3 + (0.002 \cdot Ra)^{0.26}$; $\frac{H}{\emptyset} = 0.2$ and $\emptyset = 1.2$ m |
| | | $Nu_{90} = 0.8 + (0.002 \cdot Ra)^{0.31}$; $\frac{H}{\emptyset} = 0.3$ and $\emptyset = 1.2$ m |
| | | Linear interpolation for values of H/\emptyset in-between 0.1 and 0.3 and for values of \emptyset in-between 0.6 m and 1.2 m. |
| | $\theta = 20^\circ$ | $Nu_{20} = Nu_{90}$; $0.2 \leq \frac{H}{\emptyset} \leq 0.3$ |
| | | $Nu_{20} = -0.17 \cdot (0.002 \cdot Ra)^{0.12}$; $\frac{H}{\emptyset} = 0.1$ and $\emptyset = 0.6$ m |
| | | $Nu_{20} = (0.002 \cdot Ra)^{0.19}$; $\frac{H}{\emptyset} = 0.1$ and $\emptyset = 1.2$ m |
| Linear interpolation for values of H/\emptyset in-between 0.1 and 0.3 and for values of \emptyset in-between 0.6 m and 1.2 m. | | |

2. Initiate the development of a new standard for measuring heat transfer rates in building products. This standard can be used to augment the existing ASTM hot box standards C1363, C1199, and E1324. This new experimental standard can improve the ability of experimental methods to be used in research level measurements and for validating numerical models.
3. Apply knowledge gained in this work to extend the range of correlations to products such as large commercial curvilinear products (e.g., barrel-vault skylights, very large domed skylights, etc.)
4. Incorporate results of this research into the new revisions of NFRC technical standards (NFRC 100, NFRC 200) and ISO standards (ISO 15099, ISO 10077-1, ISO 10077-2, ISO 18294).

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