Establishing the Design Process of Double-Skin Façade Elements through Design Parameter Analysis

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Abstract
The design of the double-skin façade system must consider the interactions between design parameters. The objective of this study is to propose a simple design process that considers these interactions for double-skin façades in apartment buildings in Korea. A quantitative basis was given by selecting and analyzing the design parameters related to the thermal environment. Using the Taguchi method of design of experiments, the main effects of all major design parameters and the interactions between five major parameters were revealed. The results show that the design parameters of building orientation, cavity height, cavity depth, blind position, outer skin U-value, and inner skin U-value, as well as the interaction between cavity depth and aperture size were found to be significant for total load. Based on the variance ratio of each parameter and the interactions between five parameters representing the cavity, blinds, apertures, and glass type, the design process of façade elements that considers interactions was found to be orientation - outer skin - blinds - apertures - cavity - inner skin.

Keywords: double-skin façade; design process; box-type; thermal load

1. Introduction
Just as the skin of animals and plants allows certain materials to pass through and prevents others, so the "skin" on a building is both a portal and a barrier to different natural elements. While the extra skin on the double-skin façade is in itself an additional barrier against unwanted elements within the exterior space, it also works in combination with the blinds and air cavity to form a more complex façade system. This façade system serves to prevent exterior noise, reduce wind pressures, and provide security, while at the same time allowing daylight and fresh air to enter. Its ability to use thermal uplift from solar radiation also means that the double-skin façade has a high potential for energy conservation and natural ventilation.

Among the various functions, however, the function of reducing thermal loads is involved in most of the design parameters. Therefore, a basic design process for the double-skin façade must first be established focusing on thermal aspects. The design process will be changed subsequently depending on the main purpose of the double-skin façade. In terms of thermal loads, the façade faces different conditions according to the time of year. With the change of seasons, there is a variation of outdoor temperatures, but the presence of solar radiation remains. This is further complicated by the fact that the effects of the many different design parameters interact with one another. Thus, to minimize thermal loads, the design process must consider the varying outdoor conditions and also the interactions between design parameters.

The objective of this study is to establish a simple design process for a double-skin façade that minimizes thermal loads by revealing the effects of each design parameter and assessing the interactions between the parameters of major façade elements.

2. Approach
Although the double-skin façade has been the subject of much research, the greater part of this research has focused on the evaluation of the double-skin façade system, and very little attention has been given to its design. Although the evaluation and design processes may be seen as inverses of each other, it is difficult to adopt the results of performance evaluation in design. While the evaluation analyzes the whole façade to describe how each parameter will affect the thermal load, the design must analyze how each parameter will affect the thermal load to create the whole façade. The high degree of interaction between design parameters is of little concern in evaluation, and the heat transfers may be accounted for separately, because the variables are fixed. In design, however, the variables are not fixed, and since the decision on one design parameter will affect the decisions on other parameters, they cannot be treated separately. Thus, regardless of how detailed the research on performance evaluation, it will provide minimal help in creating a design process.

Therefore, it is necessary that the design process considers the interactions between design parameters. Using multiple iterations to feedback the result of one design step as an input for another design step may be a solution. However, this involves a significant
amount of effort even for just two design parameters. Considering the numerous design parameters related to the double-skin façade, this task is virtually impossible. An alternative to this is to first analyze the effects of all of the design parameters. In doing so, the interactions between parameters must also be analyzed. Analyzing all of the parameters prior to establishing the design process is the only way to optimize the performance of the double-skin façade as a whole. The easiest way to analyze the effects of all of the design parameters is to observe the changes resulting from varying the design parameters one by one. This involves creating a base model with standard conditions, after which each parameter is changed by a certain level. The changes per parameter for several levels will be recorded, based on which the main trend of the parameter’s impact can be analyzed. Although this method will yield the most accurate results on the impact of each individual parameter, this will not convey the interactions that may or may not exist between design parameters. The most accurate way to analyze the interactions between design parameters is to provide each parameter with certain levels of variation, and then analyze all possible combinations. This is equivalent to creating a very large matrix whereby the number of dimensions is equal to the number of design parameters and the number of rows in each dimension is equal to the number of levels of variation. As can be imagined, the size of this matrix would be extremely large except when there are only a few parameters. Without an advanced calculation system to perform the analysis, this is also virtually impossible. Modern statistics provide a method which is relatively easy to use that analyzes the main effects of and the interactions between all design parameters. The Taguchi method of DOE (Design of Experiments), also known as the System of Experimental Design, was developed by Dr. Genichi Taguchi, and is often used in industries due to its major reduction in product/process development lead time. Through the use of orthogonal arrays, a limited number of cases may yield the main effect and interaction results with reasonable accuracy. Thus, the Taguchi method of using orthogonal arrays for the design of experiments is employed in this study.

3. Analysis Method
3.1 Design Parameter Selection
A box-type double-skin façade is assumed for the analysis, and the specific design parameters of the box-type double-skin façade are selected. The three modes of heat transfer, namely radiation, conduction, and convection, through the double-skin façade are reviewed, and the parameters related to each mode are identified.

(1) Parameters Related to Radiative Heat Transfer
The major concern in terms of radiative heat transfer in the double-skin façade is the influx of solar radiation because long-wave radiation does not penetrate glass. The foremost parameters related to radiative heat transfer in the double-skin façade are the properties of the outer and inner glass skins. The properties of glass related to radiative heat transfer are its transmittance, reflectance, absorptance, and emissivity. For glass, the solar transmittance is represented by its SHGC, or solar heat gain coefficient. The transmittance, reflectance, absorptance, and emissivity of the blinds are also related to the radiative heat transfer, because the blinds also form a layer that the solar radiation passes through. In addition, the position of the blinds must be considered because, unlike the glass skins, the blinds may be positioned anywhere within or outside the depth of the cavity. Although positioning the blinds on the outer surface of the outer skin is the most efficient way to reduce cooling load, this renders the blinds vulnerable to severe weathering.

With the double-skin façade, it is common practice to position the blinds within the cavity. This, however, disturbs the free flow of air during the cooling season. Positioning the blinds on the inner surface of the inner skin does not disturb the airflow, nor does it expose the blinds to weathering, but this does little to reduce the cooling load. Other parameters related to radiative heat transfer are those of the cavity floor. Assuming that the floor is not transparent, the parameters are the reflectance, absorptance, and emissivity. The area of the floor is related to how much solar radiation is reflected off the cavity floor, while the protrusion length of the cavity ceiling and the height of the cavity affect how much the cavity is shaded. Assuming that the ceiling and floor protrusion lengths are equal, the floor area and ceiling protrusion can be represented by the depth of the cavity. Thus, the parameters related to radiative heat transfer are as described in Table 1.

(2) Parameters Related to Conductive Heat Transfer
The major parameters related to conductive heat transfer are the U-values of the materials that stand between the interior and exterior. The U-values of the two inner and outer glass skins are the most obvious parameters. Because the U-value of the air layer inside the cavity cannot be a design parameter, it is omitted. However, the volume of air affects the heat capacity of the air inside the volume and hence affects conductive heat transfer. Mention should be given on how the parameters related to the influx of solar radiation also affect conductive heat transfer into the interior. Thus, these parameters are included in Table 2., which lists the parameters related to conductive heat transfer.

(3) Parameters Related to Convective Heat Transfer
Due to the nature of convection, parameters related to convective heat transfer also relate to airflow within
the façade. Thus, the parameters may be found by following the airflow path. First, the air must flow in and out, and thus the sizes of the lower and upper apertures are of primary importance. In a box-type double-skin façade, the sizes of the upper and lower apertures (which are the inlet and outlet) are equal. This is because the amount of air entering the cavity must equal the amount of air leaving the cavity. The width-to-height ratio of each aperture is important in terms of fluid dynamics, but theoretical effective areas will be assumed in this study and the width-to-height ratio will not be included as a parameter. After air has entered the cavity, the path of airflow is the cavity itself. Parameters here include the depth of the cavity and the height difference between the upper and lower apertures, as these represent the horizontal cross-section area and the length of the airflow path. Although there is ample potential for load reduction through natural ventilation during the intermediate season, the heating and cooling loads during this time are not considerable. Therefore, parameters related to the window on the inner skin of the double-skin façade are not considered. Parameters related to convective heat transfer are listed in Table 3.

4) Selection of Design Parameters

It is known that the sum of the transmittance, reflectance, and absorptance equals 1 for all materials. Also, the emissivity value is almost constant for all materials, regardless of glass types, and is not selected as a design parameter. Therefore, only one property among the transmittance, reflectance, and absorptance is used for each façade element. For glass, the SHGC (Solar Heat Gain Coefficient) of the glass is used to represent its transmittance. For blinds and the cavity floor, the reflectance values are selected as design parameters. In terms of the radiative heat transfer through the double-skin façade, as has previously been mentioned, the influx of solar radiation is the most important factor. Thus, a consideration of the amount of solar radiation is necessary. Since neither the course of the sun nor the amount of cloud cover can be controlled, the orientation of the façade is selected as a design parameter. The orientation of the façade affects how much incident solar radiation is available as well as the angle at which the solar radiation enters. Although it is less a design parameter for the façade than it is a design parameter for the entire building, the degree of impact of solar radiation compared to other design parameters will be a useful resource. Thus, the design parameters for the double-skin façade are the 12 parameters shown in Table 4.

### Table 2. Parameters Related to Conductive Heat Transfer

| Façade Element | Parameter                                |
|----------------|------------------------------------------|
| Outer skin     | transmittance, reflectance, absorptance, emissivity, U-value |
| Inner skin     | U-value                                  |
| Blinds         | transmittance, reflectance, absorptance, emissivity |
| Cavity         | depth, height, reflectance, absorptance, emissivity of cavity floor |

### Table 3. Parameters Related to Convective Heat Transfer

| Façade Element | Parameter                                |
|----------------|------------------------------------------|
| Outer skin     | transmittance, reflectance, absorptance, emissivity |
| Inner skin     | size of each aperture, height difference between inlet and outlet |
| Blinds         | reflectance, position                     |
| Cavity         | depth, height, reflectance of floor       |

### Table 4. Selected Double-Skin Façade Design Parameters

| Façade Element | Parameter                                |
|----------------|------------------------------------------|
| Outer skin     | SHGC, U-value                            |
| Inner skin     | SHGC, U-value                            |
| Blinds         | reflectance, position                     |
| Apertures      | size, height difference between inlet and outlet |
| Cavity         | depth, height, reflectance of floor       |
| Whole Façade   | orientation                              |

#### 3.2 Taguchi's Method of Design of Experiments

Taguchi's approach to parameter design provides the design engineer with a systematic and efficient method for determining near optimum design parameters for performance and cost. The objective is to select the best combination of control parameters so that the product or process is completely robust with respect to noise factors.

The Taguchi method utilizes orthogonal arrays from the design of experiments theory to the study of a large number of variables with a small number of experiments. Using orthogonal arrays significantly reduces the number of experimental configurations to be studied. Furthermore, the conclusions drawn from small scale experiments are valid over the entire experimental region spanned by the design parameter sources and their levels. Although orthogonal arrays were developed much earlier, Taguchi has simplified their use by providing tabulated sets of standard orthogonal arrays and corresponding linear graphs to fit specific projects.

In the orthogonal array, all of the columns are mutually orthogonal. That is, for any pair of columns, all combinations of factor levels occur, an equal number of times. In this study, while there are 12 parameters, it is also important to include an analysis on the interactions between façade elements. Although the $L_{27}$ (3$^{13}$) array is sufficient for the 12 parameters, it cannot account for the interactions. (The $L_{27}$ (3$^{13}$) orthogonal array can analyze 13 parameters with 3 levels using 27 simulations.) The effects of interaction between two parameters require two columns in the orthogonal array, because the degree of freedom for one parameter is 2 and the degree of freedom for interaction between two parameters is 4. If the effects of interaction between all twelve parameters must be analyzed, 122 (=$2\times C\times2$) more columns are necessary. For 134 (=122+12) columns with 3 levels, the $L_{729}$ (3$^{136}$) array must be used, which requires 729 simulations. This array is hardly ever used, due to its size. In fact, even the $L_{243}$ (3$^{121}$) is rarely used. Although the ideal solution is to use the $L_{729}$ (3$^{136}$) array, it may safely be assumed that not all of the parameters have
interactions. Also, the effects of two parameters analyzed simultaneously does to some degree reveal an interaction between the two, even when these interactions are not assigned columns. Therefore to simplify the matter, the number of interactions to be analyzed is reduced, and the L₀₉ (3⁶) array is adopted.

The five parameters for which the interactions will be analyzed must be such that provides insight into what order the design process must follow. Since it is likely that the parameters related to a single façade element will be designed together, the interactions are considered only of certain parameters representative of major façade elements. Therefore, the interactions between the following design parameters are assigned columns in the orthogonal array: depth of the cavity, aperture size, blind reflectance, U-value of the outer glass skin, and the SHGC of the outer glass skin. This is to represent the major façade elements: the dimensions of the cavity, the apertures on the outer skin, the blinds, and the outer skin itself. The levels must be defined for the twelve design parameters before simulations can be performed based on the orthogonal array. The values of these levels need not be critical values, such as the maximum or minimum or even the average, as the effects of these levels will not be used directly. However, the results of analysis will be more valuable if the values closely represent the range of values the parameters are likely to be in practice. In this study, the values for the levels are selected from typical previous built examples of double-skin façades or from typical apartment building conditions. Table 5 lists the descriptions of the levels for each design parameter. (Note: In assigning letters to represent each design parameter, E and H are not used, as they may be confused with other properties, namely e: error and H: height.)

After completion of the 81 simulations for the L₀₉ (3⁶) orthogonal array, an ANOVA (Analysis of Variance) table may be drawn. An ANOVA table usually contains the degree of freedom df, variation S, variance V, and variation ratio F, for each source, i.e. design parameter, and error.

If there are n measured values, the degree of freedom df is (n-1). This is because the number of components which can be freely changed is (n-1), since a single identity holds among the n deviations. Therefore, the number of degrees of freedom for each parameter in this study is 2, as there are 3 levels. For the interactions, the degree of freedom is 4, because the degree of freedom of each parameter is 2. Variation S is calculated as follows for all sources, the error, and the total.

\[ S_A = \frac{A_0^2 + A_1^2 + A_2^2 - CF}{27} \]  \hspace{1cm} (1)

\[ S_T = \sum_{i=1}^{81} \left( \text{simulation result} \right)_i^2 - CF \]  \hspace{1cm} (2)

\[ S_e = S_T - (S_A + S_B + \cdots + S_N) \]  \hspace{1cm} (3)

where,

Aₙ: the sum of all simulation results with level i for parameter A

\[ CF: \frac{(\text{total})^2}{81} \]  \hspace{1cm} (4)

Variance \( V \) is calculated as follows.

\[ V_A = \frac{S_A}{df} \]  \hspace{1cm} (5)

Variance ratio \( F_0 \) is calculated as follows.

\[ F_{0A} = \frac{V_A}{V_e} \]  \hspace{1cm} (6)

If the effect of parameter A is negligible, then \( V_A \) should be about \( V_e \). This means that we only need to compare \( F_{0A} \) with the value in the F-table for 2 degrees of freedom in the numerator (df of A) and the degree of freedom of the error in the denominator to determine whether or not the parameter is significant. The \( F_e \) value may thus be used in itself as a measure of how much influence a parameter has on the simulation results.

### 3.3 Simulation Model

For the simulations in this study, the commercial software TAS Building Designer of EDSL (Environmental Design Solutions Limited) is used. TAS effectively couples heat transfer and airflow iteratively. At each time step, wind pressures and wind pressure gradients are calculated for all exposed apertures. At each iteration step, the air densities in all zones are then calculated from the zone temperatures, and these are used to calculate thermal uplift pressures and uplift pressure gradients for both sides of each aperture. A set of equations is then set up describing the balance of mass flow into and out of each zone. The equations are solved using a gradient-based method to yield zone pressures and flow rates in both directions through each aperture. These flows are then fed back into the thermal analysis where they are used.

### Table 5. Level Description for Design Parameters

| Code | Design Parameter | Level 0 | Level 1 | Level 2 |
|------|------------------|--------|--------|--------|
| A    | Orientation      | S      | SE     | E      |
| B    | Height of Cavity | 3,000 mm | 2,600 mm | 2,000 mm |
| C    | Depth of Cavity  | 1,200 mm | 700 mm  | 216 mm |
| D    | Cavity Floor     | 50%    | 35%    | 20%    |
| E    | Aperture Size    | 400 mm | 200 mm | 50 mm |
| F    | Aperture Height  | 1,200 mm | 1,000 mm | 800 mm |
| G    | Difference       |        |        |        |
| I    | Blind Position   | Outside | Inside | Inside |
| J    | Blind Reflectance| 70%    | 50%    | 30%    |
| K    | Outer Skin       | 6.164 W/m².K | 2.791 W/m².K | 1.744 W/m².K |
| L    | Inner Skin       | 6.164 W/m².K | 2.791 W/m².K | 1.744 W/m².K |
| M    | SHGC of Outer Skin| 0.88 | 0.78 | 0.58 |
| N    | SHGC of Inner Skin| 0.88 | 0.78 | 0.58 |
to generate updated zone temperatures. The iterative process continues until zone temperatures converge to an accuracy of 0.01K and flow rates converge to an accuracy of 0.0005 kg/s.

The weather conditions used for the simulations are those for the Seoul area compiled by the Society of Air-Conditioning and Refrigerating Engineers of Korea (SAREK) for the years 1974 – 1983. The data includes global and diffuse solar radiation, cloud cover, dry bulb temperature, relative humidity, wind direction, and wind speed. Based on previous research, the heating period is defined as the five month period from November to March, and the cooling period is defined as the three month period from June 11th to September 10th. The indoor temperature of the residence unit of interest is selected to be within the range of 20 ~ 26°C from the comfort zone specified in the ASHRAE Fundamentals handbook. The residence unit of the simulation model is a 4.7 x 5.3 m2 living room. The floor-to-floor height is 3.2m, and the floor-to-ceiling height is 2.6m, as is the typical apartment building in Korea. One 5.3m side forms the inner skin of the double-skin façade, and the remaining sides are interior walls. For simplicity, no doors or windows have been placed on the residence unit. The materials used for the ceiling and walls of the residence unit and their thermal properties are the same as those used in typical apartment buildings. However, these will have little bearing on the results of the simulations because the residence unit is surrounded on all faces, excluding that which forms the façade, by zones of equal temperature and interior load conditions.

4. Results and Discussion

According to the Taguchi method of Design of Experiments, simulations were performed for the 81 cases described by the Lo, orthogonal array and the levels of variation shown in Table 5. The results are as described in Table 6. F-testing for these tables is performed with 2 degrees of freedom for the main effect sources, 4 degrees of freedom for the interaction sources, and 16 degrees of freedom for the error. From any conventional F table, it is noted that the 5% value is 3.63 with 2 for f1 and 16 for f2, and 3.01 with 4 for f1 and 16 for f2. Therefore, the main effect sources with a variation ratio F1 greater than 3.63 and the interaction sources with a variation ratio F2 greater than 3.01 are said to be significant. These sources are represented by shaded rows.

For the total loads, the design parameter sources that are found to be significant are A: building orientation, B: height of the cavity, C: depth of the cavity, I: blind position, K: the U-value of the outer glass skin, L: the U-value of the inner glass skin, and CF: the interaction between the depth of the cavity and the aperture size. For the heating loads, J: blind reflectance, M: SHGC of the outer glass skin, and JM: the interaction between blind reflectance and SHGC of the outer glass skin, are also significant. For the cooling loads, J, M, and also F:

| No | Cooling | Heating | Total |
|----|---------|---------|-------|
| 1  | 120.07  | 1181.42 | 1301.49 |
| 2  | 105.23  | 849.88  | 955.12 |
| 3  | 110.85  | 826.53  | 937.38 |
| 4  | 189.47  | 697.78  | 887.25 |
| 5  | 225.59  | 444.77  | 670.36 |
| 6  | 115.24  | 748.16  | 863.40 |
| 7  | 264.14  | 589.46  | 853.61 |
| 8  | 133.27  | 870.38  | 983.65 |
| 9  | 150.31  | 557.35  | 707.65 |
| 10 | 185.52  | 491.32  | 676.84 |
| 11 | 121.17  | 1101.71 | 1222.88 |
| 12 | 144.32  | 753.84  | 900.16 |
| 13 | 111.05  | 612.90  | 723.95 |
| 14 | 146.74  | 609.42  | 756.17 |
| 15 | 154.86  | 384.10  | 568.96 |
| 16 | 181.75  | 429.65  | 619.40 |
| 17 | 273.57  | 425.00  | 498.57 |
| 18 | 133.10  | 846.11  | 959.20 |
| 19 | 175.83  | 420.05  | 595.93 |
| 20 | 151.58  | 376.38  | 532.96 |
| 21 | 114.78  | 913.52  | 1028.30 |
| 22 | 221.22  | 513.33  | 734.55 |
| 23 | 125.33  | 722.05  | 847.38 |
| 24 | 218.38  | 645.23  | 863.61 |
| 25 | 114.71  | 670.95  | 785.66 |
| 26 | 187.59  | 195.74  | 383.34 |
| 27 | 182.04  | 352.00  | 534.04 |
| 28 | 117.54  | 817.91  | 935.45 |
| 29 | 146.54  | 487.66  | 634.22 |
| 30 | 159.43  | 649.70  | 809.13 |
| 31 | 222.69  | 668.17  | 890.85 |
| 32 | 188.60  | 658.46  | 896.06 |
| 33 | 113.66  | 1293.14 | 1406.80 |
| 34 | 181.31  | 482.27  | 663.57 |
| 35 | 118.20  | 690.97  | 809.17 |
| 36 | 208.15  | 522.56  | 744.11 |
| 37 | 259.97  | 388.26  | 426.23 |
| 38 | 117.85  | 862.95  | 980.80 |
| 39 | 146.33  | 499.46  | 648.82 |
| 40 | 123.63  | 868.54  | 1110.17 |
| 41 | 192.28  | 483.96  | 676.24 |
the aperture sizes are significant. An interesting point to note is that J and M are significant for both the heating and cooling loads, but are not for the total loads. An explanation for this is that J and M are related to the transmission of solar radiation, and although a better solar transmission decreases heating loads, it increases cooling loads, and vice versa. It is also noted that although F is significant for cooling loads, it is not significant for the total loads. This is because the heating load accounts for a greater portion of the total thermal load. However, F cannot be neglected in analyzing the total loads, because F is a factor in CF: the interaction between cavity depth and aperture height, and CF is significant. Table 7. lists the results of the simulations for total load according to each level of each design parameter, and they are shown graphically in Fig.1. Although all of the design parameters that are found to be significant all show a trend of increasing or decreasing proportionally with the resultant load, the combination that yields minimum loads is not clear if there are interactions among these parameters. From the orthogonal array, the load results may be expressed similarly to the graphs of Fig.2., which represent the simulation results as effects of two parameters. All combinations of the significant design parameters are included.

The graphs show that interaction exists between design parameters A and B, A and C, and B and C. Although parameter A (orientation) is not actually a design parameter, the interaction between B and C must not be overlooked. In addition, for the interaction cases of AB and BC, the minimum load result is not the intersection of the levels with the lowest effect values. In other words, although level 2 has the lowest
Fig. 2. Effects of Two Significant Design Parameters

Fig. 3. Design Process for the Double-Skin Façade
of the design parameters must also inevitably be treated together, which include K – M and L – N, because there is a limit to the types of glass available on the market, and C – D, because the depth of the cavity determines the area of the cavity floor.

For parameter L, the U-value of the inner glass skin has a very high effect value, and the façade element of the inner glass skin goes to the end of the order. For parameter A, orientation is not a design parameter, with the exception of the unlikely case where the building’s orientation is selected to improve the thermal efficiency of the façade. Also, since the building's orientation is directly related to the amount of incident solar radiation and thus is a critical factor in selecting the values for the design parameters, it necessarily belongs at the front of the design process. The resulting design process is schematically shown in Fig.3.

5. Design Process

With the effects of each design parameter and the characteristics of interaction identified, it now remains to establish the order which the design process is to follow. The interactions used in the orthogonal array, between the five parameters representative of the major façade elements, are the main basis on which the design process will be established. From Table 7., the interactions listed in decreasing the order of variance ratio F0 (from highest to lowest) are CF – JM – CJ – FK – FM – CK – CM – KM – JK – FJ. From this, it may be inferred that the design parameters in decreasing order of interaction are (from highest to lowest): C – F – J – M – K.

In designing with parameters with interaction involved, the simplest solution is to design those parameters with the least interaction first. This way, subsequent alteration on other parameters will have less of an influence on the effect of the previous design value. From the above sequence, the order in which to design for the parameters is: K – M – J – F – C. The major façade elements represented by the above five parameters are C: the cavity, F: apertures, J: blinds, and K and M: outer glass skin. Thus, the façade elements will be designed in the order of: outer glass type – blinds – apertures – cavity. Since the interactions have focused on the façade elements that affect the characteristics of the cavity, the above order does not include anything about the inner glass skin. To incorporate this element and to decide on the order for all of the design parameters, the main effect of each parameter is utilized. The variance ratio F0 is again used for this purpose. Similar to the logic behind ordering the above designing of interacting façade elements, the parameters with the least effect must be designed first. Thus, possible influence from subsequent alterations of other parameters will have less of an affect on the final thermal load.

The design parameters listed in order of increasing effect (from lowest to highest) are: G – N – J – F – D – M – C – B – A – K – L – I. This order, however, is important only after the order from interactions is satisfied: outer glass type (K, L) – blinds (I, J) – apertures (F, G) – cavity (B, C, D). Also, it must not be forgotten that the significant parameters with interaction, i.e. B – C, must be treated together. Some of the design parameters must also inevitably be treated together, which include K – M and L – N, because there is a limit to the types of glass available on the market, and C – D, because the depth of the cavity determines the area of the cavity floor.

6. Conclusion

The objective of this study was to establish a basic design process for double-skin façade elements. A quantitative basis was given by selecting and analyzing the design parameters related to the thermal environment. Using the Taguchi method of design of experiments, the main effects of all major design parameters and the interactions between five major parameters were revealed. For a simple and accurate simultaneous analysis of the design parameters, the Taguchi method of design of experiments is selected, and the L_{340} (340) orthogonal array is utilized. The effects of the parameters, orientation, cavity height, cavity depth, cavity floor reflectance, aperture size, aperture height difference, blind position, blind reflectance, U-values of the outer and inner skins, and the SHGC’s of the outer and inner skins are as illustrated in the graph of Fig.2. Based on the variance ratio of each parameter and the interactions between the five parameters representing the cavity, blinds, apertures, and glass type, the design process of façade elements that considers interactions was found to be: orientation - outer skin - blinds - apertures - cavity - inner skin. This is represented in Fig.3.

Acknowledgements

This research was supported by the Yeungnam University research grants in 2007.

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