The reasonable ways to reduce the heat losses from windows

Jia Gaoxun

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Supervisor: Taghi Karimipanah
Examiner: Nawzad Mardan
Abstract

The window insulation always plays an important role in building design and thermal comfort, it is one of the main parts needed to be optimized in building envelop. Window insulation is a basic element which can decide the insulation capacity. The large heat loss from the window is the main part of wasting energy, and simultaneously, there is also difficult to explore the new energy source and to improve the current heat generation device efficiency in this energy crisis century. Therefore, building a proper insulated window system is a good approach to keep an acceptable indoor climate as well as to reduce energy use and negative climate effects. On the other hand, there are amounts of old houses and poorly design houses all over the world either in a well developed country or a developing country. Therefore it can form a better atmosphere to optimize the window worldwide. The aim of the thesis is telling the reader what kind of optimization can be done to get better window insulation. This thesis starts with a briefly introduction to give the basic knowledge of heat loss from windows, and then shows the heat loss level in comparison with other parts of building. Afterwards it gives the optimization strategy to make good window glazing and window frames. For frame design, the hollow frame material property and the benefits of insulants filling window system are described. There are still some problems which exist for the energy efficient windows, such as condensation problem. The thesis also shows this kind of problem and the solution approach.
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1. Introduction

The section is an overview of basic thesis factors. It provides the background and research issue in order to make a clear landscape and explain what will go on with the project.

1.1 Background

Indoor climate involves lots of elements, these elements will influence the inside occupants feeling about the temperature, humidity and air quality etc. Generally speaking, there are too much details related to the sensitivity of occupants which can be described as a standard concept, the thermal comfort. Thermal comfort defined as “the condition of human mind in which satisfaction is expressed with the thermal environment”\(^{\text{\textregistered}}\). Because it is a scale that based on the occupants’ subjective feeling, therefore the sample must be a certain amount of a group of persons. And this kind scale named PMV-PPD scale (Fanger, 1970). The PMV means “predict mean vote”. It indicates a scale of feeling from cold to hot, thermal sensation scale ranging from cold (−3) to hot (+3) with neutral (0) in the middle as follows: (i) ±1: slightly warm (+) or cool (−); (ii) ±2: warm (+) or cool (−); (iii) ±3: hot (+) or cold (−); (iv) 0: neutral which is neither cool nor warm (Fanger, 1970). Then the PPD, “predicted percentage of dissatisfied” always shown as a graph curve to indicate how many percentage dissatisfy and also can be calculated by the PMV.

Widely speaking, there is more than one factor that influences the indoor climate thermal comfort. In 1962, Macpherson defined the following six factors that affecting thermal sensation: four physical variables which are air temperature, air velocity, relative humidity, mean radiant temperature, and two personal variables which are clothing insulation and activity level (Djongyang et al, 2010).

It is obviously can be notice that the indoor temperature is a really essential element of

indoor climate. Indoor temperature is not only related to the feeling of indoor staff, but also has something to do with their working efficiency. Forget about the all the science issue, the temperature in the house is always discussed in public daily life, especially for winter time. Keeping an acceptable indoor temperature related to supply heat and reduce heat loss. There is no absolutely tight building. Therefore the energy leakage can be found everywhere. Joint between different building constructions is a tricky part. The air leakage will take away the heat. Although this part is a hard to solve, it did not occupy too many percent of the total heat loss. Focusing on the windows, the window is used as a media of outside vision; also it will make the building looks beautiful. Unfortunately, heat loss from windows aspect occupied 40% of total loss (Gustavsen et al, 2011).

As an example, about 85% of single-family houses in Sweden are more than 30 years old. Windows in many of old buildings are poorly insulated and the energy efficiency is down to a bad level. Hence, it has a large potential to install energy efficient windows in existing houses. Annually 15 TWh of heating energy lost through the windows of Swedish residential buildings (Naira, 2011). Windows have a long lifespan. Therefore, the type of windows energy saving components will influence the energy use of the buildings for a long period. It is a good way to reduce the energy waste. This kind of existing poorly insulated building components, such as windows, need to be replaced, it is cost efficient to replace them with an energy-efficient component. This strategy will reduce the current energy use (Naira, 2011).

With this amount of heat loss be solved, the heating supply will decrease to a considerable level. To some degree, the district heating burden can be relieved. Furthermore, it also makes contribution to resource saving and environment control.

Still, every coin has two sizes, the efficient window may get a good low U-value, but the condensation problem will occurs, especially during cold winter morning. The wake up person cannot know what is going on with the yesterday snow, because there is wet surface window in front of them that obstruct their sight.

Therefore, a good window must contain more insulation property with fewer
drawbacks.

1.2 Purpose

The aim of this thesis is to find reasonable ways to defend the heat loss from windows, and the focal point is on the structure of the whole window. Firstly, the process focusing on the glass section, find a low U-value glazing construction. Secondly, focusing on the frame structure, explore the new method of construct the window frame. After that, discuss the exist problems when using this kind of window.

1.3 Research Question

The research question includes:
How much energy loss from the window? And what superiority the efficient window gets than normal window?
What kind of window glazing construction can help to reduce the heat loss?
What kind of window frame construction can help to reduce the heat loss?
What kind of problem emerges from energy efficient window?

2. Methodology and theory

Roughly speaking, this project is based on the existing data, and it will be integrated again to show the overall value. Therefore it includes less primary data and the analysis just spread out on the secondary data.

2.1 Data collection and analysis

Once a research problem has been formulated, the outcome is based on the data collection and analysis. To collect data, it can be divided into two parts, the primary data and secondary data (Walliman, 2005).
The secondary information usually can be found on the internet, the library, the
company record and the university database. Etc. 

During this research, the main data is directly come from the database “science direct”. It provide different efficient window model to review and discuss. The collected data is used for explain and comparison in order to make a data analysis. Because no statistics analysis included in this project, qualitative analysis can be used to indicate the property of efficient window, and shows the difference.

2.2 Research Method

There are two headings at a simple level, the former type – quantitative – refers to research that is concerned with quantities and measurement; qualitative research, on the other hand, is linked to in-depth exploratory studies, where the opportunity for ‘quality’ responses exist (Biggam, 2008). Measurements from the literature review indicate how the efficient window reduces the heat loss by using both quantitative method and qualitative method. For the outcome possible problem, taking qualitative method is enough to explain what wrong occurs.

2.3 Research Strategy

Research strategy is carried out to describe how it is intend to implement the empirical study (Biggam, 2008). Grounded theory is one of the research strategies. It is quite difficult theory to apply in practice, it is demanding in the sense that it does not follow the normal procedures for implementing a research project. In one word, the discussion and conclusion of the grounded theory based project is draw from a clear research focus and go through the other literature review which can support the topic (Biggam, 2008). In this study, the strategy is what it state above, the outcome achieve is just rely on the database and analysis.

2.4 Reliability and Validity

Valid research is all about implementing the empirical work – from selection of an
overall research strategy to the collection and analysis of the data – in a way that uses research approaches and techniques suited to each of these activities. And the central concept of the reliable empirical research is the credibility or says the degree of trust (Biggam, 2008). Because the secondary data that used in this project came from the scientific paper database science direct, therefore it contains both the reliability and validity.

2.5 Theory

To realize the heat loss from numerical, the main equation from heat transfer field can explain the detail about how a certain heating energy is losing:

The origin equation \( Q = KD (T_i - T_e) \), \( U = K/D \)

\( Q \): heat transfer rate, W

\( K \): thermal conductivity, W/mK

\( D \): the thickness of material (glass)

\( U \): the U-value of window, W/m²K

\( T_i \): The temperature inside the room

\( T_e \): The temperature outside the room

Usually, the indoor temperature is about 20°C

As states above, U-value is the key of the heat transfer. A low U-value can reduce the heat loss indeed.

Another aspect, if there is a way to reduce the air leakage from the window surrounding, then the heat loss can be reduce as well.

2.5.1 The ordinary condition (as an example) to show the difference

How much energy leakage of the window could be when compare with the other part of building construction. In well insulated buildings the U-factor of walls, roof and floors can be between 0.1 and 0.2 W/m²K. The best windows have U-factors of about 0.7–1.0 W/m²K (Gustavsen et al, 2011). Even in some old house the U-value can reach
more than 1.2 W/m²K (Nair. et al, 2011).

One example can show the difference; these three windows are common window in its research:

Window 1, U-value: 2.7 W/m²K
Window 2, U-value: 1.8 W/m²K
Window 3, U-value: 1.4 W/m²K (Nielsen, et al, 2000)

During winter time, the outside temperature \( T_e \) is treated as 0 °C.

According to the equation conversion:
\[
q_1 = 2.7 \times (20 - 0) = 54 \text{ W/m}^2 \\
q_2 = 1.8 \times (20 - 0) = 36 \text{ W/m}^2 \\
q_3 = 1.4 \times (20 - 0) = 28 \text{ W/m}^2
\]

Even for the best window, taking the number 0.7, the \( q = 0.7 \times (20 - 0) = 14 \) W/m²K

In comparison with the roof or floor, the window part is could reach almost 27 times as much than that.

3. Result of research findings

There are different optimization approaches to reduce the heat loss from windows. Both the glazing and frame can be made some change in order to reduce the convection or conduction heat transfer. This section will gradually introduce some technology or reasonable method and outcome problem then explain in detail.

3.1 Optimization of glazing

Current main technology based on the multi-layer glazing window, vacuum glazing system, gas filling window, and low-emittance coating cavity.

3.1.1 Multi-layer glazing windows

In Sweden, the window of modern buildings and not too old houses are constructed as two glazing window, but for some developing country, such as China, large amounts
of building window or single house window are still the one glazing window. The different between this two is the inside gap contains or not, it could be filling with air and other gas, or just vacuum.

A case study is done by Korea scientists (Songa, et al, 2007) about the U-value of different glazing layer, it shows an obvious changes.

It can be seen from Table 1 that with the increase of glazing layer, the U-value is decrease. It has nothing to do with what kind of frame it would be, and it has no related to what kind of assignments is done within the gap of layers.

Table 1, U-value of different glazing layer (table source: Songa, et al, 2007)

<table>
<thead>
<tr>
<th>Type of glazing</th>
<th>Required overall heat transfer coefficient (U, W/m² °C) according to the material of window frame and the minimum temperature difference ratio to satisfy the insulation performance requirement (T_DRW)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Metal Without thermal breaker</td>
</tr>
<tr>
<td>Gas layer thickness (mm)</td>
<td>6</td>
</tr>
<tr>
<td>Double glazing</td>
<td>4.19</td>
</tr>
<tr>
<td>Double glazing (Low-e)</td>
<td>3.70</td>
</tr>
<tr>
<td>Double glazing (Argon-filled)</td>
<td>4.00</td>
</tr>
<tr>
<td>Double glazing (Low-e, argon-filled)</td>
<td>3.37</td>
</tr>
<tr>
<td>Triple glazing</td>
<td>3.37</td>
</tr>
<tr>
<td>Single glazing</td>
<td>6.60</td>
</tr>
</tbody>
</table>

According to the common sense, by increasing more and more glazing, the window must be getting a good insulation property. But beyond the limitation, the weight and installation problem is coming.
3.1.2 Vacuum glazing

For double or triple glazing window, the air in the gap between each glass sheets can be extracting out to form a vacuum space. Therefore the heat transfer will minimize because of the gaseous heat transfer is negligible, and the internal vacuum space can be stable for a long period in terms of current technology.

There are apparently potential benefits of vacuum glazing. Firstly, by combination of a vacuum space and low emittance coating, a very high level of thermal insulation could be achieved. Secondly, since the insulating properties of an evacuated space are effectively independent of the width of the space, a narrow vacuum space could be constructed which get good thermal insulation and saves the whole windows volume at the same time (Collins & Simko, 1998).

It still meets the challenges in design and manufacture.

- A good thermal insulation cannot be achieved if the atmospheric pressure is higher than $10^{-6}$ pa, therefore it is essential to maintain an absolutely hermetic space with a sealed edge.
- Hermetic condition needs the temperature of around 500°C to achieve during the manufacture, the low emittance coating which used to decrease radiative heat flow between the glass sheets must be survive without degradation.
- The whole glazing is under the effect of atmospheric pressure. A glass cylinder can hold almost 100 kpa pressure different associated with internal vacuum, but it is easier to fracture for a plate glazing pane. Under this circumstance, the support pillars are considerable to build within the gap to overcome the high pressure effect. Simultaneously, the pillars are a kind of thermal bridge, it forms an approach to contact indoor and outdoor climate, which is a short cut to waste energy. There is an unbalance between support components and the vacuum space. On the other hand, the support pillars must be sufficiently small to meet the demand.
- In this vacuum design, the temperature differentials result in significant
mechanical tensile stresses. The structure must be able to withstand the
differential thermal expansion of two glass sheets. So far, there are two strategies
to deal with this problem. One is use a flexible metal edge seal that permits the
lateral movement between glass sheets, therefore the glass sheets will slide over
the support pillars and it must built a glass-to-metal seal edge; another is that the
edge of two glass sheets must be rigid fused, and requires a glass-to-glass seal, it
also should permits a little bit lateral movement. Nowadays there still tricky to
make a flexible edge for vacuum glazing (Collins & Simko, 1998).

3.1.2.1 Basic Fabrication

A sample of Collins & Simko work can be seen from Figure 1. The vacuum glazing is
made by thickness of 3 mm or 4 mm soda-lime glass with low emittance surface of
inner face; The pillars are made from a high strength, heat resistant, nickel-based alloy
named Inconel 718. They are typically 0.25 mm in diameter and 0.15 mm in height.
Based on their research of relation between the diameter and length of pillars,
typically, vacuum glazing is designed with a glass-to-glass pillar conductance of
between 0.40 W/m²K (for 4 mm thick glass, with \( p=25 \) mm and \( a=0.125 \) mm), and
1.2 W/m²K (for 3 mm thick glass with \( p=20 \) mm and \( a=0.25 \) mm)
3.1.2.2 Heat transfer process

The external heat transfer of a glazing system can be significantly complex. It contains the combination of conduction of indoor and outdoor, conduction heat transfer of support pillars, forced and natural convection, and radiation. To simplify, the main part heat transfer can be calculated by the equation: $Q = UA(T_i - T_e)$. In here, the U-value can be treated as “h”, the external heat transfer coefficient which has the same units (Collins & Simko, 1998).

According to the standards for determining heat flow through insulating glazing (ASTM, 1991), the heat transfer coefficient is treated as constant with the value 8.3 W/m²K and 30 W/m²K for the hot side and cold side respectively. The temperature
on each side is 21.1°C and -17.8°C, for standard winter condition. The result will show a highly agreement with expects (Collins & Simko, 1998).

There are not only one factor need to be consider, for the rest, which is also important, such as gaseous conduction, radiative heat flow, pillar conduction, and edge conduction still should be take into calculation.

As the experiment carry out by University of Sydney, the U-value of the vacuum glazing system can reach 0.80W/m²K for the ASTM winter conditions which is sated above that inside 21.1°C and outside -17.8°C (ASTM, 1991).

### 3.1.3 Vacuum triple-glazing

As it state above, the triple glazing window and vacuum glazing window are two advanced window system. Nevertheless, the technology is combining both of them together. In terms of the Switzerland scientists project (Manz, et al.2006), the U-value can be reduce to a less than 0.20 W/m²K value which is a highly improved project than that done by University of Sydney.

It is different from the double-glazing window. This kind of triple-glazing window introduces the stainless support pillars in the gap with the position on the edge of each glass sheets.

It still meets the same challenge of ordinary double glazing, but the triple system got more serious burden than the double system.

#### 3.1.3.1 Basic Fabrication

An example of the basic design of the triple glazing window is shown in Figure 2. In all cases, the thermal conductivity of soda-lime glass was set to 1 W/mK and the emittance of uncoated glass surfaces was set to be 0.9. The support pillar emittance was set to 0.1 and the support pillar height is 0.2 mm. The selected emittances for the coated glass inside the cavity were 0.03, 0.06 or 0.09; two or four of the surfaces in the cavities were assumed to be coated. The thermal conductivity of the pillar material was set to
either a conservative value for stainless steel of 20 W/m²K, or to a fictitious material value of 1 W/m²K. The considered pillar radii ranged between 0.1 and 0.2 mm, the pillar separation between 10 and 60 mm. Glass sheet thicknesses was set to 4 and 6 mm (Manz, et al.2006).

![Diagram of glazing setup](image)

*Figure 2. Triple glazing window sample. (figure source: Manz, et al.2006)*

### 3.1.3.2 Heat transfer process

Simultaneously, the main processes are almost the same with the double and triple glazing sample. The group shows the result by computer simulation, they forming a 20 K temperature different between indoor and outdoor. In this case, 80% of the total flow through the glazing is due to heat conduction in the support pillars. Finally, the result of thermal transmittance is 0.2 W/m²K (Manz, et al.2006).

### 3.1.4 Gas filled glazing

This kind of optimization is filling gas with good thermal property between each
glazing and gets a reduction of heat loss. The most common material is absorbing gas, the rest are silica aerogel, cromogenic materials and phase change materials (PCM) (Ismail, et al. 2007).

Usually, the gas filled window can be fill with lots kind of gas, these gas sometime are noble gas or some simple gas such as the carbon dioxide (see Figure 3). For safety and valid, the filled gas must be non-toxic, low conductivity and get high viscosity.

![Figure 3, the gas filled window sample (figure source: University of Minnesota, Center for Sustainable Building Research)](image)

The window in Figure 3 is done by University of Minnesota, the noble gas argon is filled in the window. This kind of window be designed to reduce heat loss while admit the solar gain, it has low emissivity glass which can reduce heat loss in winter and refuse outdoor heat come inside in summer. In terms of the project, the U-value is achieved around 0.3 W/m²K (Arasteh. et al).

Another great research is to fill in glazing cavity with SF₆, CO₂, NO₂ and NH₃ or some other gases. The range of the width between each glazing was set from 6 to 20 mm, and kept at a steady state; uncoated clear-silica glass has a hemispherical surface emittance of 0.84. In coated-glass case, the surface of the glass which expose to indoor was assume to have an emittance of 0.065; the convergence criteria requires that the heating energy flux leaving the exterior surfaces agree to within 0.5 W/m²K with each other, and the residual from each energy balance be less than 0.2 W/m²K.
The heat transfer process includes energy conducts, transmits, absorbs and emits thermal radiation.

During the modeling, their result in Figure 4, Figure 5 and Figure 6 shows the relation between the gap width and the U-value.

**Figure 4**, The relation between gap width and the U-value of CO$_2$ as media

**Figure 5**, The relation between gap width and the U-value of SF$_6$ as media
Figure 6, The relation between gap width and the U-value of $NH_3$ as media

From the result, it obviously that the U-value decrease with the increase of the gap width, and with low emissivity coating of 0.065, the U-value is more acceptable than the high one.

It is better to keep the low emissivity coating of 0.065 and control the width around 16-20 mm.

3.2 Optimization of window frame

The new strategy of construct the frame is built a hollow frame with insulants filled in. It improves the insulation function of the frame and save the material.

3.2.1 The common frame material

Many types of materials are used to construct the window frame. The most popular materials are timber, polymer and metal (Aizan, et al. 2008).

There is amounts kind of frame material with the U-value:

- Balsa: 0.055 W/m²K
- Cypress: 0.097 W/m²K
- Fir: 0.11 W/m²K
Maple or Oak: 0.166 W/m²K;
Yellow Pine: 0.147 W/m²K;
White Pine: 0.112 W/m²K;
PVC (polyvinylchloride): 0.09 W/m²K;
Aluminum alloy (Al-Mg-Si): 177 W/m²K (Holman, 2010).

To date, the polymer plays an important part in energy saving design of window frame. As shown above, it got a relative low U-value when compare with some timber. It also gets both light and high strength property that better than some low heat transfer rate timber, because some of them get worse strength.

Still the aluminum alloy frame can be found everywhere in some old house in country like China. Both of the window and door frame of some new house even constructed by the aluminum alloy. From the value indicates, this kind of window do bad in energy saving. To some degree, they just got the property of beauty and safe.

3.2.2 Frame fabrication and simulation result

The research of filling different insulants in different kind of frame is done by some Norway scientists. They do the simulation method to get the possible result. There are totally five kind of window that named as A, B, C, D, E (see Figures 7-11). For the basic design, all the frames were simulated with triple glazing. 95 percent argon and 5 percent air filling in the cavity, and set two low-e coatings with an emissivity of 0.037. The resulting glazing U-factor was 0.710 W/m²K. For all of the frames, the spacer effective conductivity was varied between 0.02 W/mK and 10 W/mK. The temperature boundary condition is that inside 21°C and outside -18°C (Gustavsen, et al.2011).
Figure 7, foam insulation aluminium frame (figure source: Gustavsen, et al.2011)

The cross-section of frame A (Figure 7) (thermal broken aluminum): The purple elements show the placement of the polyurethane (PUR) foam. The light green elements show the unventilated cavities of the frame. The dark blue elements show the frame's aluminum skeleton. The thin layer of aluminum cladding covers solid polyurethane elements, minimizing direct connections between inside and outside. It is calculated the thermal transmittance values for various configurations of spacers which effective conductivity ranging from 0.02 to 10W/mK. Thermal insulation conductivities is detected from 0.005 to 0.089 W/mK for the frame (Gustavsen, et al.2011).

Figure 8, thermally broken aluminium frame (figure source: Gustavsen, et al.2011)

The cross-section of frame B (Figure 8): The black elements show polyamide thermal
breaks (with 25% glass fiber of thermal conductivity 0.173 W/mK) and the light blue area represents the aerogel (with thermal conductivity 0.057 W/mK). The light green elements are the unventilated air cavities within the frame. The blue and dark red elements depict the outer and inner aluminum skeleton, respectively. The outer aluminum skeleton has an emissivity of 0.9, and the inner one has an emissivity of 0.6. The performed calculations for various combinations of spacer and thermal break conductivities. The spacer effective conductivity was varied from 0.02 to 10 W/mK, and the thermal break conductivity was set from 0.005 to 0.173 W/mK (Gustavsen, et al. 2011).

Figure 9, foam insulated wood frame (figure source: Gustavsen, et al. 2011)

The cross-section of frame C (Figure 9): The pink areas show the placement of the PUR insulation material, it is insulated with a continuous 17-mm-thick layer of PUR foam, and the brown areas represent the wood (nodic pine with thermal conductivity 0.12 W/mK) areas of the frame. The light green elements are the unventilated air cavities within the frame. The performed calculations for various combinations of spacer and thermal break conductivities indicate the spacer effective conductivity was varied between 0.02 and 10 W/mK, and the thermal break conductivity from 0.005 to 0.029 W/mK (Gustavsen, et al. 2011).
The cross-section of Frame D (Figure 10): Solid core wood is shown in brown. Air cavities are shown in light green. The spacer effective conductivity was varied between 0.02 and 10 W/mK, and the wood conductivity from 0.005 to 0.12 W/mK (Gustavsen, et al.2011).

The cross-section of Frame E (Figure 11): The brown areas show the PVC skeleton of the frame, and the light green areas show air cavities. The blue areas show the supporting steel and the continuous parts of the hardware used for opening the frame.
The calculations for various effective spacer conductivities from 0.02 to 10 W/mK, and PVC surface emissivities between 0.02 and 0.9. Hollow inside frame could be a control group (Gustavsen, et al.2011).

Overall situation, the group gives out the total window U-factor as figure. Figure 12 shows the variation in total window U-factor as a function of spacer conductivity. Figure 12 shows the total window U-factor as a function of material/thermal break conductivity and emissivity (Gustavsen, et al.2011).

![Figure 12](image)

*Figure 12, Total window U-factor from A to E*

The light grey denotes the minimum U-factor for the whole window. The dark grey bar shows the range of U-factors found by varying the frame material property between the minimum value and the default real material value. A spacer with an equivalent conductivity of 0.25 W/mK is used for these results. The horizontal line in the light grey bar denotes the U-factor found when using the minimum material property (emissivity and frame material conductivity) and a spacer equivalent conductivity of 0.02 W/mK. It can be observed that the best condition of these window all get the U-value less than 1 W/m²K.

**3.2.3 Another fabrication and result**

From the appearance, the above strategy is obviously not neat enough. The frame
inside construction is complex and sometimes cause confused. A neatly frame design is carry out by some Ireland scientists. They built a symmetry and triangular skeleton which make the entire work simple and beauty.

There are different kinds of frame material and insulants material be simulated during the research. All of them can be found in Table 2, the structure design is shown in Figure 13. Consider about the strength and maintenance, the material to be test from metal to wood and polymer, also a table is included as reference. Each one of these material do not get strength, low maintenance rate, low thermal conductivity at the same time.

Table 2, the frame material and cavity insulants (table source: Fang, et al. 2003)
The simulations of the indoor and external ambient air temperatures were set to 21.1 °C and −17.8 °C respectively. The convective heat transfer coefficients on the indoor and the outside surfaces were set to 8.3 W/m²K and 30 W/m²K, related to measurement standards for winter conditions (ASTM, 1991). The cross-sectional height of the evacuated glazing set was 0.5 m with each glass pane being 6 mm thick. The metal edge seal width was set to 10 mm. The dimensions of the frame from Figure 13 were $H = 40$ mm, $w = 50$ mm, $x = 3$ mm, $y = 30$ mm and $z = 17$ mm (Fang, et al. 2003).

### 3.2.3.1 Thermal performance of different cavity insulants

During the research, each of the selected material was set to simulation and got the relation graph of Figure 14. In the simulations, the exoskeleton material was controlled as 3 mm thick polypropylene. The results presented that increasing the insulant thermal conductivity from 0.024 W/mK to 0.068 W/mK leads to an increase by 0.63 W/mK in the heat transfer coefficient of the frame area and an increase by 0.09 W/mK in the total window system (Fang, et al. 2003).
3.2.3.2 Thermal performance of different exoskeleton material

The infill material used was controlled as expanding foam, with thermal conductivity of 0.024 W/mK. The performance can be seen in Figure 15.

The heat transfer coefficient of the vacuum space was set to be 0.4 W/mK. It can be seen from Figure 15 that increasing the frame exoskeleton thermal conductivity from 0.09 to 0.35 W/mK leads to an increase by 1.06 W/m²K in the heat transfer coefficient.
of the frame area and an increase by 0.09 W/m²K in the overall window system (Fang, et al. 2003).

In the end, they also compare the thermal performance of a single material frame and complex multi-material frame by taking wood and polypropylene as example (see Figure 16). The expanding foam was set as the filling material for the multi-material frame.

![Figure 16. Thermal performance of window with polypropylene or wood frame (figure source: Fang, et al. 2003)](image)

And as it can be easily predicted, the single material frame insulation property is worse than a complex insulants filling one.

**3.3 Possible exist problem and experiment**

**3.3.1 New phenomenon introduction**

Water condensation on windows is a common problem for public. It always can be seen between the window panes or on the inside. In both cases, the condensation indicates that the window is of poor quality or has a high U-value. For poor quality window, humid air leaks into a space that is supposed to be closed or properly ventilated. In the latter case water condenses on the inner window surface because the window is considerably colder than the room. That means there is certain heat loss out from the room through the window (Werner&Roos, 2007).
High efficient window always equipped with some kinds of energy saving material. Low-emissivity and solar control coatings in windows can considerably reduce the energy needed for heating and cooling buildings. The heat conductance of such windows, the U-value, can be as low as 1 W/m²K. For the glazed area of a window, values down to 0.5 W/m²K can be realized. In some climates, especially the climates in northern parts of Europe, where the radiative cooling towards a clear night sky can be high, this has led to a new phenomenon: external water condensation on windows (Werner, et al, 2007). It is experienced when the temperature of the external glass pane of a window goes below the outside dew point due to radiative cooling. It is appears during clear nights on well-insulated windows for which the thermal losses do not balance the radioactive cooling of the external glass surface (Werner&Roos, 2007).

As Werner said, at most case, the condensation on the window indicates a bad thermal insulation condition. But for some energy efficient window, because of it contain low emittance coating or other new technology material, it is a sign of excellent thermal insulation property as more water drops appears (Werner&Roos, 2007).

3.3.2 Sample test

The test carry out with three glass sample: uncoated clear float glass with surface emissivity 0.84 as a reference since most windows of today do not have any external coating. A low-emissivity fluorine-doped tin dioxide hard coating with surface emissivity 0.15, because it is often used on internal surfaces, and a titanium dioxide coated self-cleaning glazing product with surface emissivity 0.84 since it has the desired hydrophilic properties (Werner&Roos, 2007).

There are three cases on the process of comparison:

- High and low emissivity test
  
  To explore if there is a simple way to monitor surface temperature and to visually discern external condensation on glass samples exposed to a clear night sky. Also test whether there is a simple way to compare different coated glass samples to see
which one is more prone to condensation.

The experiment was undertaken during night with outdoor air temperature about 13 °C. Two glass samples, an uncoated clear float sample and a tin dioxide-coated clear float sample, of size 5 cm×10 cm of equal thickness were heated to about 50 °C and placed horizontally on a piece of polystyrene. A thermocouple below each sample measured the temperature. The heating to 50 °C was done to monitor the difference in cooling rate more clearly. The experiment started at midnight.

- **Horizontal test of three samples**
  To compare condensation proneness and properties of three commercial glass samples, two of them were the same as in the first experiment. Also to study how the temperature of a clear float sample and a tin dioxide-coated glass sample varies with the air temperature and relative humidity. Three (30 cm×30 cm) glass samples of equal thickness were placed horizontally with back of a piece of polystyrene, insulated from below and exposed to the clear night sky. A thermocouple below the clear float and the tin dioxide coated glass measured their temperatures. The TiO₂ surface has a same emissivity with one of uncoated glass and it can be assumed that it had the same temperature as the uncoated sample. The samples were not pre-heated as in the first experiment. A lamp was installed above the samples to provide a reflected image for the photographs. There was almost no wind.

- **Vertical test of three samples**
  To compare condensation proneness and properties of the same three commercial glass samples in an almost vertical position. Three (30 cm×30 cm) glass samples (clear float, tin dioxide-coated and titanium dioxide-coated glass) of equal thickness were placed almost vertically outdoors with back of polystyrene. They were exposed to the clear night sky without wind. Their temperatures were not measured (Werner&Roos, 2007).

**3.3.3 Testing outcome**

In their first experiment, the time that condensation occurred on clear float glass and
dioxide-coated glass are 40 min and 3h respectively of exposure to the clear night sky. There is no condensation on dioxide-coated glass during first 90 min, even when the time that condensation occurs, water on dioxide-coated glass is considerably less. The condensation in both cases took place at a surface temperature of approximately 12 °C.

In their second experiment, 1 h after sunset, the clear float and the tin dioxide-coated samples already got condensation. Meanwhile the titanium dioxide-coated glass sample had none. There are some drops of water had formed on the clear float sample. After another half an hour, there was still no condensation on the titanium dioxide-coated glass. Tin dioxide-coated sample condensates more than clear float sample. After two more hours, there are much more difference on three surfaces. The tin dioxide-coated sample had a lot of water and the titanium dioxide-coated glass sample had a haze like small condensation which was clearly wet. The condensation degree on uncoated sample looked like something in between the layer on the tin dioxide-coated and the layer on the titanium dioxide-coated glass. And condensation seems to have occurred at approximately the same temperature of 12°C.

In their third experiment, the Figure 17 can tell the different. The three samples are set outside all the night, there is certain condensation on the surface, but Figure 17 shows the titanium dioxide-coated glass got a better vision to see through (Werner&Roos, 2007).

![Figure 17, The condensation on clear float, tin dioxide-coated and titanium dioxide-coated glass respectively (figure source: Werner&Roos, 2007)]
4. Discussion

It can be observed that the with the glazing layer increase the glazing U-value will decrease. Just because of multi-glazing layer contain gaps between each glazing, therefore no matter what kind of insulation material filling inside, it has a certain insulation function. The single glazing window do not have gaps, much energy will be lost. It obviously save twice as much heat loss with the triple glazing system of U-value of 2.6 W/m²K when compare with the single glazing got a value of 5.3 W/m²K. If a quadruple-glazing window system can be built, it will get three gaps. At that condition, the insulation function must be considerable great no matter the insulation gas filling in or not.

There are not too many words to talk about the low E coating, because it is just a small particle in this field, but it still indicates this kind of coating is necessary to contain in the glazing optimization. There is a certain difference when the glazing system add a low e coating material, in terms of Figure1, compare with the double glazing with U-value of 3.30 W/m²K, a low e coating coated one got a 2.90 W/m²K which reduce almost 14% heat loss.

The gas filling glazing is an advanced improvement when compare with the common glazing-air-glazing window, it take the advantage of the space and the compressive of gas. Insulation gas is easy to moving, filling, and did not obstruct the vision. In terms of Arasteh’s group and Reilly’s group research, they both got a satisfactory result for their gas filling glazing research. Nevertheless, what makes the different is Arasteh’s group adopts the noble gas while Reilly’s group chose some ordinary gas. The noble gas may be really expensive, but it has stable chemical property and bad heat transfer property, their result got an excellent value of 0.3 W/m²K. At the same time, the material from Reilly’s group does not have that low value. According to their relation figures, the U-value could reach a low condition by ignore the glass thickness. As the example shows in Figure5, the SF₆ filling window with low e coating material of
0.065 sample may reach 0.7 W/m²K with the glazing thickness of 20 mm. The common sense tells that a piece of glazing over 10 mm is really thick let alone the 20mm one. But in the feasible thickness range, it still got less than 1.5 W/m²K which means it still a really good value. On the other hand, SF₆ is cheaper than argon, it is more acceptable by public.

The frame can be designed as the profile of symmetry or irregular that depends on how the insulants will be constructed inside. Insulants associated with the cavity may result in a better insulation property. It can be found that, in the Gustavsen’s group work, the histogram Figure 12 tells the glazing system D get the best insulation function which is made by solid wood frame and cavity inside. The histogram also tells that after install the frame, the glazing U-value will decrease. It can be found in Figure 12, some of the window such as sample A, C, D and E, the U-value of glazing with frame is lower than glazing without frame. That means it must found a frame which can compensate the glazing. By the way, the small elements spacer in the research that related to the glazing optimization also proved how important it is. By notice the horizontal line in the Figure 12, the total U-value decrease some, after change the 0.25 w/mk one to the 0.02 W/mK one. In their construction work, the spacer built at the edge between each glazing. Recalling the vacuum design in glazing optimization chapter, it is the same with Manz’s group did in Figure2. This kind of support pillar will not cause some vision problem. But when it comes to the Collins & Simko’s work, their spacer distributed uniformly between two glazing (Figure1), even the pillars are also made by glass, it still obstruct the vision somehow, which is an old and defective design.

The symmetry frame design done by Fang’s group looks neatly than Gustavsen’s group work. It also gives out that simple principle: less thermal conductivity, less heat loss. The thermal conductivity of expanding foam in Table.2 is 0.024 w/mk, each low U-value sample is filled by it (Figure14). On the other hand, polyvinyl chloride shows a good insulation function during all kinds of frame material, in Figure15. As it
performed, the lowest U-value sample frame is covered by it. It is also essential to compare the difference between filled frame and single material frame. The last work of Fang’s group denotes the rule of complex multi-material frame got the better thermal performance than single material frame window.

Every coin gets two sides. The energy efficient window also has trouble of condensation, but this kind of condensation is new, because it is the outside external surface condensation. The researcher Werner aims to carry out work on glazing covered material to solve the problem rather than do the structure work of the whole window system. It is really a good strategy, because it will not cause bad influence on the window, also avoid the extra new problem occurs. It can be observed that the titanium dioxide-coated glass performs well in each testing experiment. It may condensates but the surface is still clear and obstructs less vision.

5. Conclusion and outlook

Back to the topic, to get a better indoor temperature with less heating supplied at the same time, it is essential to build a space with less heat loss which means the common large heat loss part, such as window part must be optimized in order to meet the demand.

According to all researchers’ work, the insulation strategy should be focus on the window glazing and frame at the same time, each of them cannot be missing or ignore. On the glazing part, multi-glazing layer is much better than single glazing, it can be found that triple glazing window always got a better insulation performance in every research. Therefore to date, the focus should be change towards the triple-glazing because the double one will be replaced step by step. What is more, the gap between two glazings also cannot be ignored, no matter filling in some insulation gas or extract the air to get a vacuum space. For gas filling strategy, it is better to use the noble gas such as argon, but if the cost of whole window system cannot be accept, the gas can
be change to some cheap compounds also with a stable chemical property, such as SF$_6$.

For vacuum space strategy, the support pillars should be placed on the edge, therefore, it will not obstruct the vision.

Window frame must be optimized at the same time. Frame with single material will not be considered, and it is the same with the metal frame, because both of them will cause either bad insulation or inside surface condensation. Hollow inside with insulants filled frame is the best choice, with wood or PVC covered, an expanding foam filled frame will performance very well.

At last, low emissivity coating is another important element which worked to reduce heat loss in winter and refuse outdoor heat come inside in summer. And the coating material must be paid attention, because low U-value efficient window meet the external surface condensation problem, the titanium dioxide-coated glass will do a favour to solve this problem.

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