The Effect of Windows on Thermal Comfort

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Degree Thesis

Distributed energy systems

2016

EXAMENSARBETE	
Arcada	
Utbildningsprogram:	Distribuerade energisystem
Identifikationsnummer:	
Författare:	Roy Karanen
Arbetets namn:	The Effect of windows on thermal comfort
Handledare (Arcada):	Kim Skön
Uppdragsgivare:	Mikael Paronen

Sammandrag:
I examensarbetet strävar jag att svara på frågorna; Hur påverkar fönster och dess olika egenskaper den termiska komforten. Och med vilka åtgärder kan man förbättra de egenskaper fönstret har, som påverkar den termiska komforten.
I kapitel två kommer jag att gå igenom värmeöverföring med diverse överförings metoder och i slutet på kapitlet behandlar jag kort termisk jämvikt. Tredje kapitlet behandlar termisk komfort, bestämmande av komfort och vilka faktorer påverkar komforten. I slutet av kapitlet behandlar jag ett par matematiska modeller man använder för att förutse om ett klimat är komfortabelt eller inte. Fjärde kapitlet behandlar termisk asymmetri och vilka de största påverkarna för termisk asymmetri är. Det femte kapitlet behandlar fönster och dess egenskaper och hur dessa påverkar den termiska komforten. Kapitlet behandlar också hur man kan förbättra dessa egenskaper hos fönstret. I det sjätte kapitlet kommer jag att diskutera hur fönstrets egenskaper påverkar termiska komforten i olika klimat och på vilka sätt det går att förbättra fönstrets påverkan på den termiska komfort zonen.
Examensarbetet baserar sig på de fynd jag gjort från; publiserad literature, standarder och nätsidor, som behandlar termisk komfort och fönster prestanda.

Nyckelord:	Termisk, Komfort, Fönster, asymmetri, förbättra
Sidantal:	8+41
Språk:	Engelska
Datum för godkännande:	02.06.2016

DEGREE THESIS	
Arcada	
Degree Programme:	Distributed energysystems
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Author:	
Title:	The Effect of windows on thermal comfort
Supervisor (Arcada):	Kim Skön
Commissioned by:	Mikael Paronen

Abstract:

In my thesis I will try to answer the questions; Which of the windows' characteristics affect the thermal comfort zone and which steps can be made to improve these characteristics. In the beginning there will be a short introduction of the subject Windows and thermal comfort. In the second chapter I will run through heat transfer and the three heat transfer modes and end the part with thermal equilibrium. The third chapter will be about thermal comfort, determination of climate comfort and the six factors that affect the comfort in a climate zone. In this chapter I will also show the mathematical equation that is used to predict if a climate will be comfortable or not. The fourth chapter will treat thermal asymmetry, what it causes and how thermal asymmetry is caused. In the fifth chapter I will present how window characteristics affect thermal comfort and how the characteristics of the window can be improved. In the sixth and final chapter I will discuss how the characteristics of a window affect the thermal comfort zone in hotter and cooler periods and how to make the most of the windows characteristics during these periods.
This thesis is based on the findings I have done from published literature, standards and webpages that treat the subject of thermal comfort and window performance.

Keywords:	Thermal comfort, Windows impact on thermal comfort, thermal assymmetry
Number of pages:	8+41
Language:	English
Date of acceptance:	02.06.2016

OPINNÄYTE	
Arcada	
Koulutusohjelma:	Hajautetut energiajärjestelmät
Tunnistenumero:	
Tekijä:	Roy Karanen
Työn nimi:	The Effect of windows on thermal comfort
Työn ohjaaja (Arcada):	Kim Skön
Toimeksiantaja:	Mikael Paronen

Tiivistelmä:

Opinnäytetyössä pyrin vastaamaan kysymykseen; miten ikkuna ominaisuudet vaikuttavat lämpöviihtyvyyteen ja miten voidaan parantaa ikkunan vaikutusta lämpöviihtyvyyteen.
Alussa opinnäytetyö käsittelee lämmönsiirron ja sen eri tilat, luvun lopussa käsittelen mitä lämpöenergian tasapainotila on. Kolmas luku käsittelee lämpöviihtyvyyttä ja siihen liittyvät tekijät. Luvussa käsittelen myös matemaattiset kaavat mitä kaavoja käytetään kun määritetään alueen viihtyvyyttä. Neljännessä luvussa puhutaan termisestä epäasymmetriasta ja mitkä ovat isoimmat tekijät tällä alueella. Viidennessä luvussa käydään läpi ikkunoiden ominaisuuksia ja miten ne vaikuttavat termiseen viihtyvyyteen. Tässä luvussa käydään myös läpi miten voidaan myös parantaa ikkunoiden eri ominaisuuksia. Viimeisessä luvussa keskustelen miten ikkunan ominaisuudet, vaikuttavat lämpöviihtyvyyteen ja miten voidaan tehostaa tai parantaa ikkunan ominaisuuksia.
Opinnäytetyö perustuu tuloksiin jotka olen löytänyt; kirjallisuudesta, standardeista ja verkkosivuilta.

Avainsanat:	Lämpöviihtyvyys, Ikkuna, ominaisuudet, parantaa, epäsasymmetria.
Sivumäärä:	8+41
Kieli:	Englanti
Hyväksymispäivämäärä:	02.06.2016

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1 INTRODUCTION

This work try's to answer the question: How does a window affect our climate comfort zones? One of the objectives has been to make every aspect as simple as possible, so that people without prior knowledge regarding this area, would still be able to understand.

The work starts with an introduction to thermal comfort and what factors it is governed by. Mathematical models, that have been adopted as standards are presented. The work will shortly address thermal asymmetry, what it is and how windows can cause thermal asymmetry. Thereafter, window properties that affect thermal comfort are studied in more detail.

On basis of the data from various published and online sources, including experiments done in this field. I will explain how a window impacts the thermal comfort zone.

2 HEAT TRANSFER

Heat transfer is the exchange of thermal energy between two or more physical systems, thermal energy in transit. The heat flows from the warmer system to the cooler system, both systems strive after thermal equilibrium. When both systems have the same temperature they are in equilibrium and there will be no heat transfer. There are three fundamentals modes of heat transfer: conduction, convection and radiation.

2.1 Conduction

Conduction occurs when heat is transferred from a warmer body to the cooler body. The heat transfers from body one to body two, by interaction of particles at the molecular level in the medium.

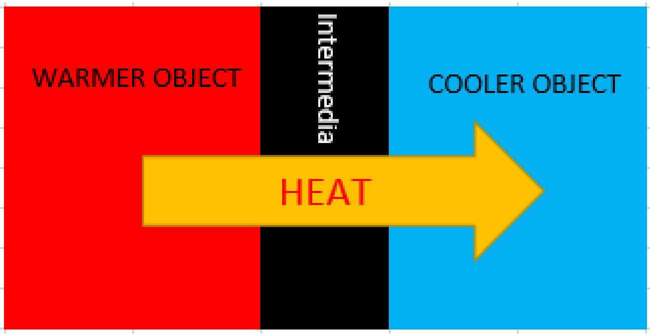

Figure 1. Conductive heat transfer diagram

(2.1)

To calculate the heat transfer rate we need to know how much the heat flux is.
The heat flux is determined as

> *"[...]the heat transfer rate in the x direction per unit area perpendicular to the direction of transfer ,and it is proportional to the temperature gradient dT/dx , in this direction" (Fundamentals of Heat and Mass Transfer 6th edition)*

And is obtained by Fourier's law of heat conduction.

$$\dot{Q}_{cond} = -kA\frac{\Delta T}{L}$$

Where $\dot{Q}_{cond}$ is the heat flux, k is the thermal conductivity for a material, A is the heat transfer area, L is the thickness of the medium and ΔT is the temperature difference,

2.2 Convection

Thermal transfer by convection occurs when we have the heat transported from one place to another by moving fluids or gases, transfer of heat via mass transfer.
Waterborne climate systems utilize convection when cooling and heating buildings.
Convection and conduction usually appear in a system that transfers heat "together".
The rate of convection heat transfer can be determined by Newton's law of cooling.

$$\dot{Q}_{conv} = hA_s(T_s - T_\infty)$$

Where $\dot{Q}_{conv}$ is the convective heat transfer rate, h is the convection heat transfer coefficient, A_s is the surface area from which the heat transfer takes place, T_s is the surface temperature and T_∞ is the temperature of the fluid that is has in an adequate distance from heat source.

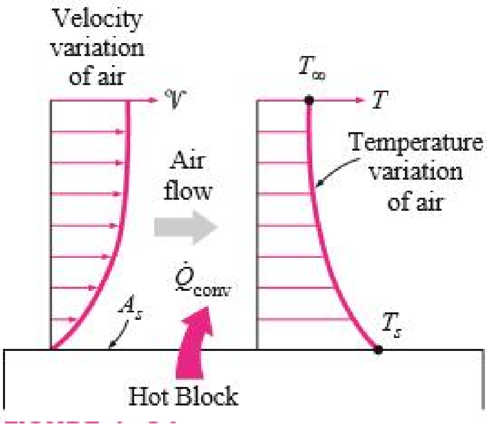

Figure 2. Diagram over convection cooling.

Convection is seldom without conduction and the other way around, thermal energy is not bound to one mode while in transit.

2.3 Radiation

Radiation is the third heat transfer mode, and does not need any medium to transfer energy, can transfer heat through vacuum. The energy is transferred in electromagnetic waves. An objects rate of transfer of radiant energy in vacuum can be determined by the Stefan-Boltzmann law.

$$\dot{Q}_{emit,max} = \sigma A_s T_s^4$$

Where $\dot{Q}_{emit,max}$ is the maximal emitted energy from the source, $A_s$is the emitting surfaces area, T_s^4 is the emitting surfaces temperature and σ is the Stefan-Boltzmann constant.

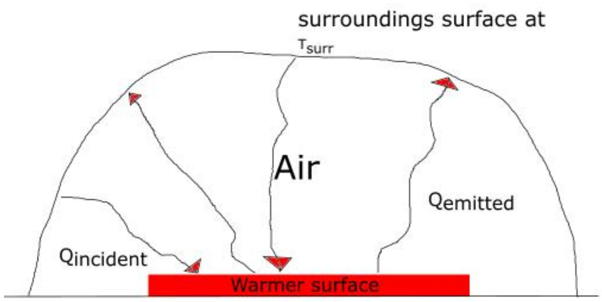

Figure 3. Diagram over radiations capability to transfer heat through vacuum

The radiation heat transfer is dependent on the properties of the surface, how they are oriented relative to each other, and how the medium interacts with radiation.

Direct radiation is traveling in a "strait line" towards the target. While diffuse radiation is radiation resulting from obscured and reflected rays.
Solar radiation is both direct and diffuse radiation. The radiation is diffuse in both clear and cloudy days, due to scattering of the solar beam when entering our atmosphere. The sun's direct beams reach the surface if it is un-obscured; the direct beam has more intensity if they fall direct on a surface and is reduced greatly when the angle to the surface gets bigger.[1] In the figure below, solar diffuse and direct radiation is illustrated.

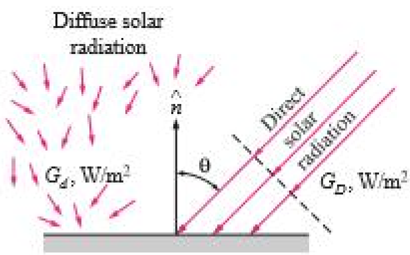

Figure 4. Direct and diffuse radiation occurrence on a horizontal surface

The sun is not the only surface that emits thermal radiation surfaces that are heated by other means than from the sun, also emit thermal radiation.

[1] Encyclopedia of Geomorphology

2.4 Thermal equilibrium

Zeroth law of Thermodynamics states that if two systems are at the same time in thermal equilibrium with a third system, they are in equilibrium with each other.

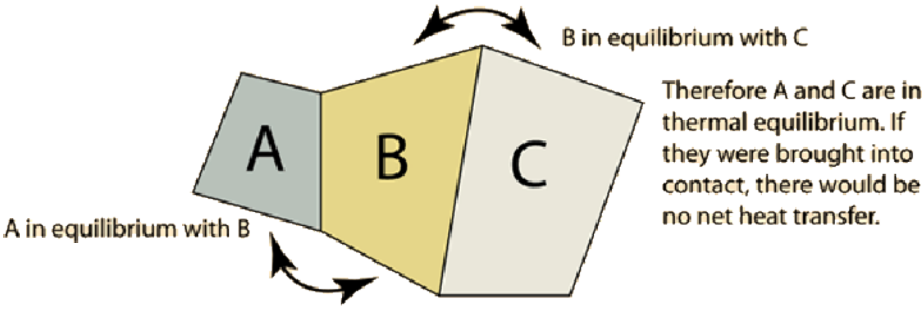

Figure 5. Diagram over equilibrium according to Zeroth law of thermodynamics

The figure can be used to visualize a double paned window, if we agree that C is the inside panel B is the gas (argon) between the glass panes and A as the second and outer glass panel. The more resistance we give the heat the longer it will take to reach that equilibrium.

3 THERMAL CLIMATE COMFORT

Climate comfort is as the name suggests an indoor climate factor that is determined by experienced feelings in a climate zone by humans. There are many variables in the surrounding that have a direct impact on thermal comfort, we will return to these variables later in this work.

Even if thermal climate comfort is a factor based on how a person or a group experience the climate, determination of a good or bad comfort climate is standardized and can be found in both: International Organization for Standardization (ISO), American National Standards Institute and American Society of Heating, Refrigerating, and Air-Conditioning Engineers ANSI/ASHRAE standards.

3.1 Determination of Thermal Comfort

Determination of the climate comfort is standardized and is determined by using mathematical equations, given in both ISO 7730-2005 and ANSI/ASHRAE standard 55.
In ISO 7730-2005 the Thermal Comfort is defined as,

> *That condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation.*[2]

The data for evaluation of thermal comfort is gathered by "here and now" standardized surveys. There are comfort models that make "here-and-now" predictions over the likely answer of a group in a certain environment, the input data is based on the answers of the surveys.
It is hard to satisfy everyone due to variation in metabolic rate and other physical variants. Thus, thermal comfort is not the same for everybody.
There are six primary factors that must be addressed when defining conditions of thermal comfort: (ASHRAE Standard 55)[3]

1. Metabolic rate
2. Clothing insulation.
3. Air temperature.
4. Radiant temperature
5. Air Speed.
6. Humidity.

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[2] ISO 7730:2005(reviewed 2015) / 3rd edition
[3] ANSI/ASHRAE Standard 55-2013

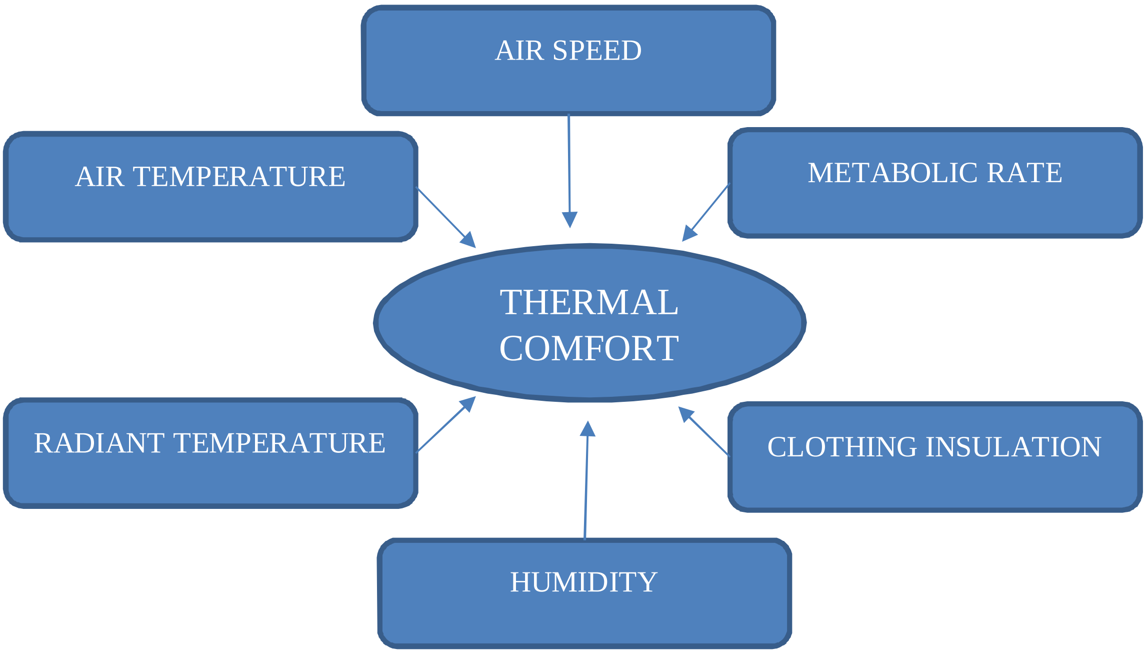


Figure 6. Diagram over factors governing thermal comfort

3.2 The six primary factors

In this part we are going to go through the six different factors, in the same order as from ANSI/ASHRAE standard 55, which must be addressed when defining the thermal climate comfort, and why they are taken into measure. The primary factors can be into two categories, Environmental and Personal variables.

The ISO 7726 Thermal environments: instruments for measuring physical quantities, tells us the requirements for measuring instruments that are needed to determine some of these six factors. Excluded clothing insulation and metabolic rate.

Some of the environmental factors, the radiant temperature and air temperature are used to calculate the operative temperature. To get an acceptable accuracy on the operative temperature, for persons in near sedentary activity, not in direct sunlight and are not exposed to air speeds greater than 0,2m/s. The following equation is suffice to calculate the operative temperature meeting these criteria's.[4]

$$T_{operative} = \frac{T_{air} + T_{radiant,mean}}{2}$$

Where T_{air} is the air temperature and $T_{radiant,mean}$ is the mean value of all radiant temperatures in the zone.

3.2.1 Metabolic rate

Metabolic rate is defined in a medical dictionary as,

> *Metabolism per unit time especially as estimated by food consumption, energy release as heat, or oxygen used in metabolic processes.*[5]

As a case study: At a factory we have two workers, one of them is lifting products by manual labour and the other worker is writing down what products go where. The person doing manual labour has a higher pulse and uses energy from his reserve to perform the work, and his metabolic rate is high because the energy releases as heat. The second worker is standing still and does not have an elevated metabolic rate and thus his body is not generating heat. The worker that does the manual labour might think the temperature is good or on the warmer side, while the worker writing thinks it is more on the cold side.

So metabolic rate is the body's heat power production and is measured in the unit MET, what stands for Metabolic Equivalent of Task. Listed in the table below, heat generated by the human body and corresponding MET value for some physical activities.

[4] ANSI/ASHRAE Standard 55-2004,page 10

[5] Definition of metabolic rate http://www.merriam-webster.com/medical/metabolic%20rate (1.3.2016)

Table 1. Metabolic rates for activities

Activity	Metabolic rate	
	W/m^2	met
Reclining	46	0,8
Seated, relaxed	58	1,0
Sedentary activity (office, dwelling, school, laboratory)	70	1,2
Standing, light activity (shopping, laboratory, light industry)	93	1,6
Standing, medium activity (shop assistant, domestic work, machine work)	116	2,0
Walking on level ground:		
2 km/h	110	1,9
3 km/h	140	2,4
4 km/h	165	2,8
5 km/h	200	3,4

The standards use metabolic rate instead of basal metabolic rate because of variation of labour sorts. Basal metabolic rate is defined as followed in a medical dictionary

The rate at which heat is given off by an organism at complete rest.[6]

The different between these two might seem small but when defined there is a clear different.

3.2.2 Clothing Insulation

All thermal insulation work with the same laws of physics: heat moves from warmer areas to the colder areas, insulation is only slowing down this process.

Air pockets that your clothes form will resist the transfer of heat, but not stop the loss nor gain of heat totally.

The insulation you get from clothes work with the same principle that insulation in buildings, with some diversity, to get a thermal heat resistance that keeps the body from emitting a heap of thermal energy into the surrounding air. Clothing insulation can be expressed in **clo** units or as m^2KW^{-1}, where m^2 is the SI-unit of area and KW^{-1} is the thermal resistance unit temperature, divided by the power.

[6] Definition of Basal metabolic rate

1clo will maintain an inactive person at 1 met continually comfortable, in the environment of 21 °C, RH 50% and air speed of 0,01 m/s.
The more stagnated air the clothes maintain around the body, the warmer the clothes are.
In the table below you can see the thermal insulation for typical clothing combinations.

Table 2. CLO values for clothing combinations

Work clothing	I_{cl} clo	I_{cl} $m^2 \cdot K/W$	Daily wear clothing	I_{cl} clo	I_{cl} $m^2 \cdot K/W$
Underpants, boiler suit, socks, shoes	0,70	0,110	Panties, T-shirt, shorts, light socks, sandals	0,30	0,050
Underpants, shirt, boiler suit, socks, shoes	0,80	0,125	Underpants, shirt with short sleeves, light trousers, light socks, shoes	0,50	0,080
Underpants, shirt, trousers, smock, socks, shoes	0,90	0,140	Panties, petticoat, stockings, dress, shoes	0,70	0,105
Underwear with short sleeves and legs, shirt, trousers, jacket, socks, shoes	1,00	0,155	Underwear, shirt, trousers, socks, shoes	0,70	0,110
Underwear with long legs and sleeves, thermo-jacket, socks, shoes	1,20	0,185	Panties, shirt, trousers, jacket, socks, shoes	1,00	0,155
Underwear with short sleeves and legs, shirt, trousers, jacket, heavy quilted outer jacket and overalls, socks, shoes, cap, gloves	1,40	0,220	Panties, stockings, blouse, long skirt, jacket, shoes	1,10	0,170
Underwear with short sleeves and legs, shirt, trousers, jacket, heavy quilted outer jacket and overalls, socks, shoes	2,00	0,310	Underwear with long sleeves and legs, shirt, trousers, V-neck sweater, jacket, socks, shoes	1,30	0,200
Underwear with long sleeves and legs, thermo-jacket and trousers, Parka with heavy quitting, overalls with heave quilting, socks, shoes, cap, gloves	2,55	0,395	Underwear with short sleeves and legs, shirt, trousers, vest, jacket, coat, socks, shoes	1,50	0,230

3.2.3 Air temperature

The air temperature tells us how warm it is in the room and from that we can calculate the amount of energy there is and brought in to the room or climate zone. In other words, tells us if we are cooling the space or adding heat to the room.

If we had a climate zone and our initial tests has shown that people experience the zone warm. We could easily cool down the zone by decreasing the temperature of the incoming air, to the point that there would be a neutral sensation amongst the people.
When we add cooler air into the room, convection cooling would occur and cool down the room. In other words the thermal energy would transfer from the warmer parts into the cooler air.

3.2.4 Radiant temperature

Radiant temperature tells us the temperature of radiating object. In a room we have four walls, they have absorbed thermal energy and starts emitting thermal radiation. Every surface has its own temperature that it emits, so instead of treat every surfaces temperature individually, we determine the Mean Radiant Temperature (MRT) to work with[7]. We can estimate the MRT by calculating it using an equation.

$$MRT = T_1 F_{persone-1} + T_2 F_{persone-2} + \cdots + T_N F_{perosne-N}$$

Where:

MRT: Is the mean radiant temperature

T_i: is the temperature of the surface

$F_{Persone-i}$: Is the view factor between the occupant and surface i.

[7] ANSI/ASHRAE standard 55-2004. page 6

Or can measure the radiant temperature using a globe thermometer. The convective heat exchange has to be taken in concern when measuring temperatures with this thermometer. The temperature that we get from this thermometer is not the mean radiant temperature, but we can easily obtain it from the globe temperature.[8]

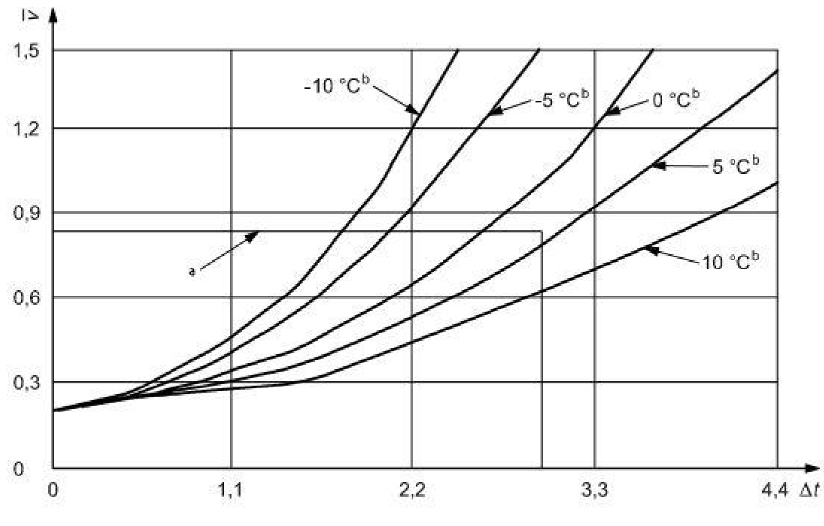
$$MRT = globe\ temperature + 2{,}42 \cdot air\ velocity\ (cm/s)$$

3.2.5 Air Speed.

The air speed affects the rate of convective heat exchange between the occupant and the environment. At higher air velocity the thermal comfort is influenced by draft and can lead to local thermal discomfort.

Increasing the air speed is one way to get excess heat out from a room or building, due to the increasing rate of convective heat exchange. This increase in air speed can be obtained by opening a window or increasing the velocity on the air handling unit.

At higher temperatures, increased air speeds up to 1m/s has been shown to feel pleasant.[9]



[10]

Figure 7. Figure over increased air velocity's effect on temperature (ref point: 26°C 0.20 m/s)

In ISO 7730:2005 there is a figure over increased air velocity effects the temperature. The x-axis is the differential temperature obtained by increasing the air flow on the y-axis.

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[8] NovaLynx Globe thermometer instruction manual
[9] Arens et al. (1998)
[10] ISO 7730:2005 Annex G

To get a comfortable thermal climate increasing the air velocity, to get a higher rate of heat transfer, is more effective when the mean radiant temperature is high and the temperature of the air is low. Elevated air speed is less effective to obtain a comfortable thermal climate if the air temperature is higher than the mean radiant temperature.

3.2.6 Humidity

The humidity has only a small effect on thermal sensation and on the air quality in room's whit inactive occupancy.[11] The body's most efficient way of cooling itself down is by sweating, when the metabolic rate rises and the body starts to produce more heat the core temperature rises. It is not the sweating itself that cools down the person, but the sweat evaporating from the body.[12]

Relative humidity (RH) is the concentration of water in the air, relative to the temperature. It is the RH that determines at which rate the air can evaporate the water from the skin, if the air is nearly saturated it becomes harder for the air to evaporate the sweat.[13]

$$RH = \frac{actual\ vapor\ density}{saturation\ vapor\ density} \cdot 100\%$$

In more warm humid environments the body depends on getting the excess heat out by sweating, when the relative humidity is high the air is not capable of receive the water and evaporating cooling is not able to occur and cool down the core temperature.

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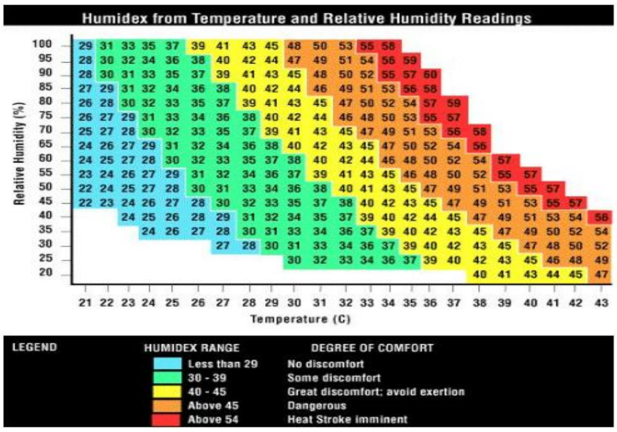
[11] EN 15251:2006, Indoor environment

[12] https://theaggie.org/2013/11/07/the-science-behind-sweating/

[13] http://www.achooallergy.com/learning/the-effects-of-humidity-on-the-human-body/

The heat index below shows how hot the temperature feels in correspondence with the RH. On the x-axis we have the actual temperature and on the y-axis we have the relative humidity. To find the humidex first find the temperature follow that line until it intersects with the relative humidity.

Table 3. Temperature and relative humidity readings (humidex)



As shown excess humidity can have another impact than only a sticky climate and the risk of mildew.

Very low humidity (RH<15-20%) causes dryness and irritation of eyes and air ways. [14] Breathing dry air can cause breathing disorders such as; asthma, inflammation in the nasal cavities and nosebleeds. Dry air can also lead to dehydration, when the fluids are depleted during breathing.[15]

3.3 Mathematical models

There are mathematical models that can predict if a comfort zone is good or bad, using the six listed benefactors in the standards (ISO 7730 and ANSI/ASHRAE 55).

The standardized models are, Fangers Predicted Mean Vote (PVM), which predicts the satisfaction of a comfort zone and Fangers Predicted percentage of Dissatisfied (PPD) that predicts the dissatisfaction of a comfort zone.

There are also comfort models that take a more adaptive approach to this mater.

[14] ANSI/ASHRAE 55-2013

[15] http://www.infoplease.com/ipa/A0001433.html

3.3.1 Predicted Mean Vote

Let's recap how thermal comfort is defined, so we can understand what we seek by using the PMV-model,

> *"That condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation. " (ANSI/ASHRAE Standard 55-2010)*[16]

The PMV is an index that predicts the mean value of the votes of a larger group of people, on a sensation scale that goes from -3 to +3, based on the heat balance of the human body. When the internal heat production of the body is equal to the loss of heat to the environment, thermal balance is obtained.

+3 hot
+2 warm
+1 slightly warm
0 neutral
–1 slightly cool
–2 cool
–3 cold

Figure 8. Seven-point thermal sensation scale

We are given three ways to obtain the PVM value.[17]

1. Using the equation

$$PMV = [0{,}303 \cdot \exp(-0{,}036 \cdot M) + 0{,}028] \cdot \left\{ \begin{array}{c} (M-W) - 3{,}05 \cdot 10^{-3} \cdot [5733 - 6{,}99 \cdot (M-W) - p_a] - 0{,}42 \cdot [(M-W) - 58{,}15] \\ -1{,}7 \cdot 10^{-5} \cdot M \cdot (5867 - p_a) - 0{,}0014 \cdot M \cdot (34 - t_a) \\ -3{,}69 \cdot 10^{-8} \cdot f_{cl} \cdot [(t_{cl} + 273)^4 - (\overline{t_r} + 273)^4] - f_{cl} \cdot h_c \cdot (t_{cl} - t_a) \end{array} \right\}$$

[16] ANSI/ASHRAE 55-2013
[17] ISO 7730:2005

Where M: the metabolic rate, W: the effective mechanical power, p_a: water vapour partial pressure, t_a: the air temperature, t_r: the radiant temperature, h_c: convective heat coefficient, f_{cl}: the clothing surface area factor.

2. Directly from Annex E from 7730:2005, where tables of PVM values are given.
3. By direct measurement, using an integrating sensor (equivalent and operative temperatures)

The PMV addresses the six primary factors, which must be taken in concern when defining the conditions for thermal comfort.

Even if the PMV is used in standards, does not mean that the model is without restrictions. The PMV does not predict the comfort for an individual person, because people have different perceptions of warmth.[18] The predicted percentage of dissatisfied (PPD) is an index that forms a measurable prediction of the percentage of thermally dissatisfied people determined from the PMV.[19]

Predicted percentage dissatisfied (PPD)

It is good to be able to anticipate the number of people whom likely will feel uncomfortable in a climate zone. The PPD is an index that predicts the percentage of people dissatisfied in the thermal environment, these would be the people that will vote in the PVM scale (fig9) anything other but 0 (neutral). The PPD value is calculated with the determined PVM value using the following equation.

[18] The validity of ISO-PMV for predicting comfort votes in every-day thermal environments
[19] ANSI/ASHRAE Standard 55

$$PPD = 100 - 95 \cdot \exp(-0{,}03353 \cdot PMV^4 - 0{,}2179 \cdot PVM^2)$$ [20]

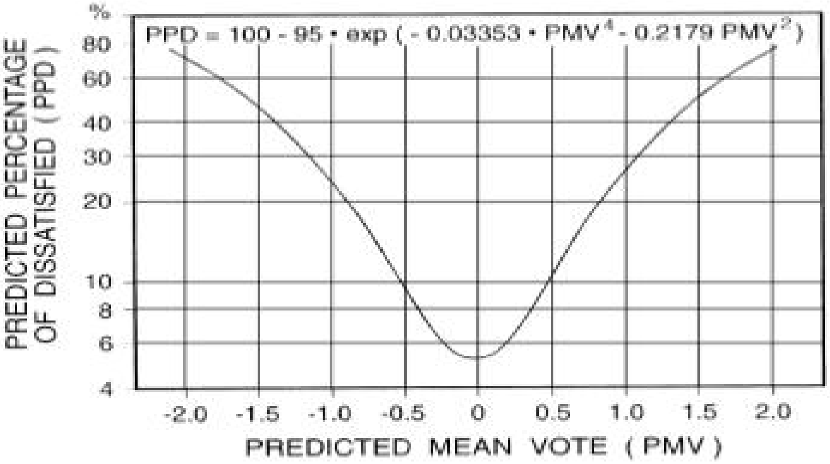


Figure 9. PPD as a function of PVM

[20] ISO 7730:2005

4 THERMAL ASYMMETRY

Thermal asymmetry is defined as.

Lack of equality or equivalence between parts or aspects of something, lack of symmetry [...].[21]

Thermal asymmetry is in other words, lack of equivalence in thermal energy between the bodies.

Thermal asymmetry is a very distinguishable factor in thermal climate comfort, the variation of temperature does not need to be great. Already a small variation of the surrounding temperature will be noticeable and potentially lead to a less comfortable climate. Thermal asymmetry is so noticeable that it can even be used to find nerve damage in a human body.

> *The degree of thermal asymmetry between opposite sides of the body (ΔT) is very small. For example the value of ΔT for the forehead (mean ± standard deviation) was 0,18 ◦ ± 0,18◦C, for the leg 0,27 ◦ ± 0,2◦C and for the foot it was 0,38 ◦ ± 0,31◦C [...] The ΔT's reported here were obtained from 40 matched regions of the body surface of 90 asymptomatic normal individuals. These values can be used as a standard in assessment of sympathetic nerve function, and be the degree of asymmetry is a quantifiable indicator of dysfunction. (Neurosurg, 1988)* [22]

Radiant asymmetry causes also discomfort, people are more sensitive to thermal asymmetry caused by higher temperature ceilings and cooler walls. In 1985 a study to define the limits for cool ceiling and hot/cool walls to which man can be exposed to without discomfort.[23] It seemed that people was more sensitive to cool wall than to the warm wall, because of this the authors stated, that local cooling of the body is causing more frequently discomfort than local heating. The limits, presented as radiant asymmetry temperatures for the ceiling are 14°C (cool)/ 23°C (warm) and for the wall 10°C (cool)

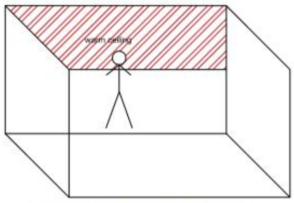
The following equations are given in ISO 7730:2005 to determine the percentage of dissatisfied.

[21] Definition of thermal asymmetry
[22] Quantification of thermal asymmetry
[23] Fanger et.al 1985, Comfort limits for asymmetric thermal radiation.

Warm Ceiling

$$PD = \frac{100}{1+\exp(2{,}84-0{,}147\cdot \Delta t_{pr})} - 5{,}5$$

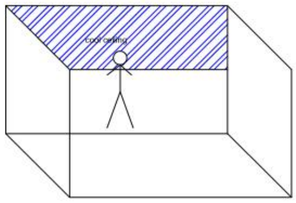
$\Delta t_{pr} < 23°C$



Cool ceiling

$$PD = \frac{100}{1+\exp(9{,}93-0{,}50\cdot \Delta t_{pr})}$$

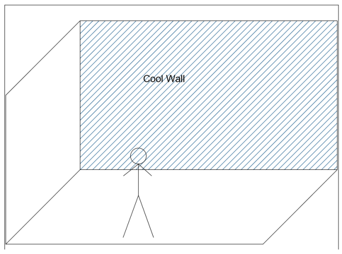
$\Delta t_{pr} < 15°C$



Cool Wall

$$PD = \frac{100}{1+\exp(6{,}61-0{,}345\cdot \Delta t_{pr})}$$

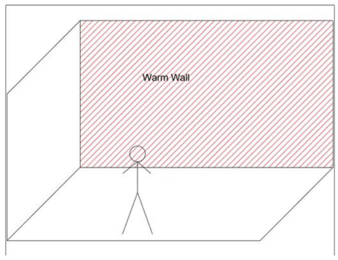
$\Delta t_{pr} < 15°C$



Warm wall

$$PD = \frac{100}{1+\exp(3{,}72-0{,}052\cdot \Delta t_{pr})} - 3{,}5$$

$\Delta t_{pr} < 35°C$



The equations “Warm wall” and “warm ceiling” have been adjusted to account for discomfort not caused by radiant asymmetry. And all of the equations were derived from the original data using logistic regression analysis, and should not be used beyond ranges shown above.[24]

[24] ISO 7730:2005, 6.5 Radiant asymmetry.

5 WINDOWS

Windows are the weakest point in a building, regarding energy efficiency and thermal resistance. So that the window would not emit all energy out from the buildings, by inserting more glass panes and inert gases between the panes to obtain the greatest thermal resistance possible. .

$$R_{tot} = R_{conv1} + R_{glass} + R_{conv2} = R_i + \frac{L}{kA} + R_o$$

Where R_{tot} is the total thermal resistance, R_{conv} is the convection resistance, R_{glass} is the resistance for the glass. R_i is the inner convection resistance, L is the thickness of the glass, k is the conductivity for glass, A is the area and R_o is the outer convection resistance.

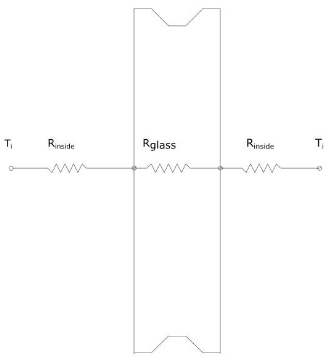


Figure 10 illustrated Thermal resistance in a single pane window

The windows impact on the thermal comfort zone is dependent on the time of the year. In the summer energy passes through the window more as thermal radiation from the sun, the thermal radiation is not restricted by the U-value of the window. A single pane window’s inside surface temperature is not affected from the heat flux due to radiation during the warmer nor colder periods.

During the winter the comfort is dependent on the inside surface temperature of the window, this can be rated directly on basis of the U-value (thermal conductivity) of the window. [25]

[25] WINDOW PERFORMANCE FOR HUMAN THERMAL COMFORT

5.1 Properties of windows

In this chapter we are going to look more on what attributes can make a window more efficient in keeping the comfort zone pleasant and what properties makes a window meet the demands.

5.1.1 U-value

The U-value determines how much energy passes through an area.

$$\dot{Q} = U \cdot (T_{in} - T_{out}) \cdot A$$

Where Q is the heat flux, U is the u-value, T_{in} is the indoor temperature (° C), T_{out} is the outside temperature (° C) and A is the glazing area of the window (m^2)

Instead of measuring every spot on a window we get a mean value for the window, we multiply the u-factor with the area of the window and we have the heat loss for the window. The U-value is the reciprocal of the total thermal resistance, a smaller U-value means that less thermal energy moves through the window and has the unit W/m^2K

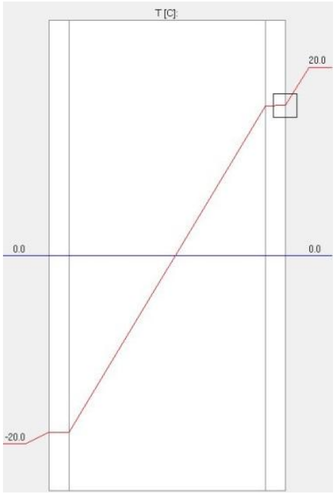
How does the effect of the U-value show up in our daily lives at home or at work? If we have a bad U-value, a high U-value, we get an increased amount of energy moving through the window. This leads first of all to a lower surface temperature and the second effect of a bad u-value is higher costs to keep the desired temperature in this space the window is in and therefore the whole building.

When the u-value is known, the heat flux can be calculated using the equation introduced in the beginning in this chapter.

$$\dot{Q}_{U=0.78} = 0.799 \cdot (20 - (-20)) \cdot 1 = 32\,W$$

$$\dot{Q}_{U=1.75} = 1.75 \cdot (20 - (-20)) \cdot 1 = 70\,W$$

The window with a lower u-value (0.799) has 120% lower heat flux and a heat loss of 103.43 kWh in a year. Comparing the annual heat losses, the window with a u-value of 1.75, has an annual heat loss of 232 kWh, which is 143% more than the window with a u-value of 0.799. The isothermal curve is shown in the figure below, with surface temperature data for both windows.



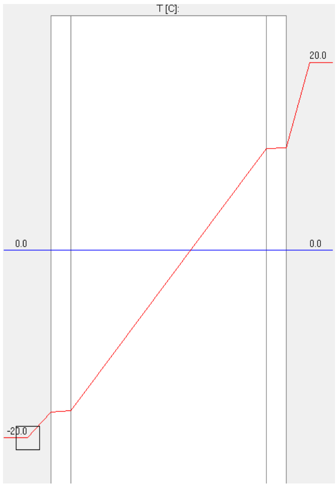


Figure 11. Isothermal curve, for window with u-value 0.799 (left). Isothermal curve, for window with u-value 1.75 (right).

Table 4.Surface temperatures for window u-value 0.799 and 1.75

U-value/surface temp °C.	0.799	1.75
Outside	-20	-20
Surface outside	-18,75	-17.20
Surface inside	15,95	10,91
Inside	20	20

5.1.2 Air leakage

Air leakage occurs when the insulation around the window frames is damaged or insufficient. Thermal energy will be free to pass through the gaps, made by damaged insulation, with close to none thermal resistance, causing under cooler periods the near vicinity of the leak to cool down and the feeling of draft. During the warmer periods heat is capable of entering the zone, leading to a higher heat load.[26]

Air leakages can be determined by thermal imaging and with pressurizing the building you might get even more out of the thermal image.

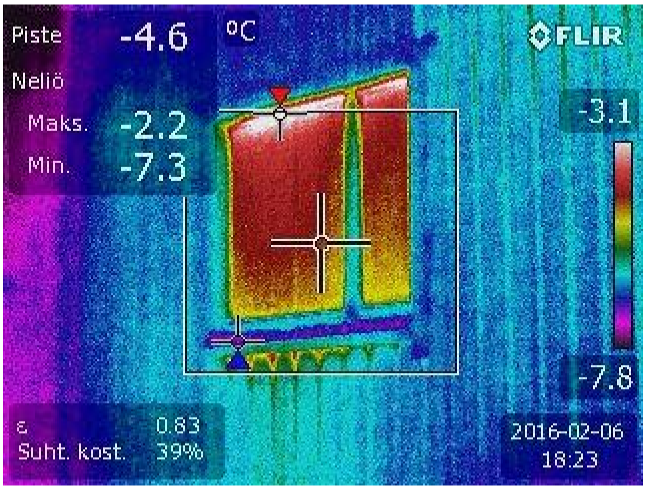


Figure 12. Thermal image of a window; note the excess heat loss at the bottom

[26] Integrated System for Economical High Performance Glass Windows & Doors

5.1.3 Transmittance

Transmittance is the amount of decreased solar radiation that managed passing through the material. In other words it's the decrease of radiation intensity through a layer known as Beer's law.[27]

$$dI_\lambda(x) = -K_\lambda I_\lambda(x)dx$$

Where I_λ is the spectral radiation beam intensity, dx is the thickness and κ_λ is the spectral absorption coefficient of the medium.

When solar radiation hits an object's surface, in our case a window, part of it is reflected from the surface, a part is absorbed by the mass of the glass and the rest is transmitted to the inner zone.[28] The first law of thermodynamics states that any energy cannot be destroyed nor created, it can only be transformed.[29] This means that the sum of the transmitted, absorbed and reflected energy should be the same as the solar radiation intensity.

$$\tau_{sol} + \rho_{sol} + \alpha_{sol} = 1$$

Where τ_{sol} is the transmissivity, ρ_{sol} is the reflectivity and α_{sol} is the absorptivity.

As seen in figure 13 some of the absorbed energy moves also inwards to the zone, by calculating the energy obtained via the transmitted (τ_{sol}) and the absorbed (α_{sol}) that is later re-emitted from the window we get the solar heat gain for the window.

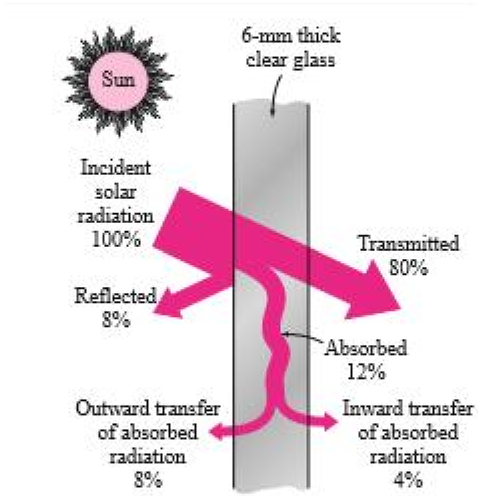


Figure 13. The solar radiation distribution on a clear glass

[27] Heat and mass transfer, a practical approach 3rd edition, page 641
[28] Heat and mass transfer, a practical approach 3rd edition
[29] http://hyperphysics.phy-astr.gsu.edu/hbase/thermo/firlaw.html

By increasing reflection of the window, with tints or selective coating we get less absorption and transmittance in to the room that leads to less direct solar heat gain.

Every material and object has their own absorption and reflection.[30]
A spectrally selective coating should ideally have a small impact on the transmittance of visible spectrum, so that the view and natural lighting would be preserved and still be almost opaque at other wavelengths.[31]
An opaque surface has little to no transmittance therefore the absorption (α_{sol}) and reflection (ρ_{sol}) will be the sum of incoming thermal radiation.

$$\alpha_{sol} + \rho_{sol} = 1$$

[30] Heat and mass transfer a practical approach.3rd edition
[31] FINAL REPORT TO THE NATIONAL FENESTRATION RATING COUNCIL FEBRUARY 2006

5.1.4 Absorption

Absorption (α_{sol}) is the sum of thermal energy that the windows mass absorbs from solar radiation and the thermal energy reflected from the ground.

$$\alpha_{sol} = 1 - \rho_{sol} - \tau_{sol}$$

The absorption does not get higher or lower even if the temperature of the window would alter but is more dependent of the temperature of the thermal radiation source. [32] As seen in the figure below absorptivity of aluminium increases with the sources temperature and the absorptivity of concrete decreases. Metals have the characteristics to absorb more when the temperature of the emitting surface is higher.[33]

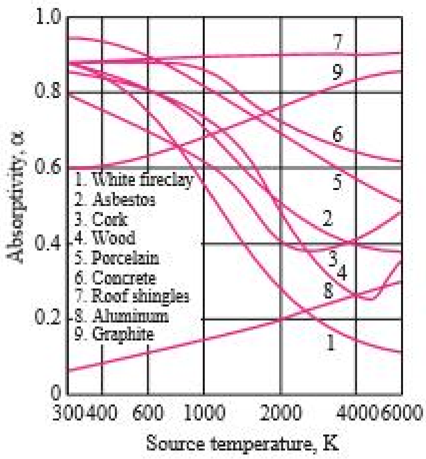


Figure 14. Absorptivity's of various materials at room temperature as functions of the temperature of the radiation source.

Different selective coating gives the window different characteristics, to reduce or increase radiation losses. Selective coating that increases the loss of solar radiation have a high emissivity and coating with low emissivity minimizes the loss of solar radiation and absorption is maximized. Nontransparent selective coating is used when the goal is to absorb thermal radiation and their emissivity is in the spectral region of radiation losses. Transparent coating has a high reflectance for long-wave infrared radiation and transmits the visible solar radiation effectively.[34]

[32] Heat and mass transfer a practical approach.3rd edition
[33] Heat and mass transfer a practical approach.3rd edition
[34] Selective Coating. (n.d.) *The Great Soviet Encyclopedia, 3rd Edition*.

As earlier discussed altering a windows capability to absorb, changes the amount of energy transmitted indoors. The energy absorbed in the window is dependent on the windows surface conditions, the internal energy will strive for thermal equilibrium and the thermal energy will mostly move to the cooler surface.[35] Heat absorbing glass can raise the MRT with up to 8°C in summer conditions.[36]

5.1.5 Emissivity

Emissivity is the surface's ability to emit radiant energy compared to a black body with an equivalent area at the same temperature[37].

A window with low emissivity (ε) reflects the incoming solar radiation much more effective and a window with a higher ε does not reflect the thermal radiation as much. Most regular windows have an emittance of 0.84[38], meaning that only 16% of the solar radiation is reflected away and the rest is transmitted or absorbed through the window. Low ε windows can reach as low values as 0.04[39], this type of window would reflect up to 96% of the solar radiation. Windows and other objects that absorb heat, typically emit the heat in the long-wave far-infrared spectrum.[40] These both are in the wave-length above and under the visible spectrum.

To reduce the short-wave solar radiations impact on a comfort zone spectral selective coating can be added to windows. And to reduce the transit of thermal radiation we want to use windows with lower emissivity, or install tints and selective coating on the windows.

5.1.6 Solar heat gain

Solar heat gain is the increase in temperature due to thermal radiation of the sun, and is dependent on the total solar irradiance (solar constant), which value is ~1373W/m^2 and

[35] Heat transfer and thermal radiation modelling page 15
[36] FINAL REPORT TO THE NATIONAL FENESTRATION RATING COUNCIL FEBRUARY 2006
[37] Heat and mass transfer a practical approach.3rd edition
[38] FINAL REPORT TO THE NATIONAL FENESTRATION RATING COUNCIL FEBRUARY 2006
[39] http://www.efficientwindows.org/lowe.php
[40] https://beopt.nrel.gov/sites/beopt.nrel.gov/files/Integrated%20Window%20System.pdf

varies by 3.5% depending on the time of the year. When the sun is closest to earth (January 3) the solar irradiance is 1418 W/m^2 and 1325 W/m^2 when the earth is farthest away from the sun (July 4 at 40° latitude).[41]

Table 5. Hourly variation of solar radiation incident on various surfaces and the daily totals throughout the year at 40° latitude

		Solar Radiation Incident on the Surface,* W/m^2															
		Solar Time															
Date	Direction of Surface	5	6	7	8	9	10	11	12 noon	13	14	15	16	17	18	19	Daily Total
Jan.	N	0	0	0	20	43	66	68	71	68	66	43	20	0	0	0	446
	NE	0	0	0	63	47	66	68	71	68	59	43	20	0	0	0	489
	E	0	0	0	402	557	448	222	76	68	59	43	20	0	0	0	1863
	SE	0	0	0	483	811	875	803	647	428	185	48	20	0	0	0	4266
	S	0	0	0	271	579	771	884	922	884	771	579	271	0	0	0	5897
	SW	0	0	0	20	48	185	428	647	803	875	811	483	0	0	0	4266
	W	0	0	0	20	43	59	68	76	222	448	557	402	0	0	0	1863
	NW	0	0	0	20	43	59	68	71	68	66	47	63	0	0	0	489
	Horizontal	0	0	0	51	198	348	448	482	448	348	198	51	0	0	0	2568
	Direct	0	0	0	446	753	865	912	926	912	865	753	446	0	0	0	—
Apr.	N	0	41	57	79	97	110	120	122	120	110	97	79	57	41	0	1117
	NE	0	262	508	462	291	134	123	122	120	110	97	77	52	17	0	2347
	E	0	321	728	810	732	552	293	131	120	110	97	77	52	17	0	4006
	SE	0	189	518	682	736	699	582	392	187	116	97	77	52	17	0	4323
	S	0	18	59	149	333	437	528	559	528	437	333	149	59	18	0	3536
	SW	0	17	52	77	97	116	187	392	582	699	736	682	518	189	0	4323
	W	0	17	52	77	97	110	120	392	293	552	732	810	728	321	0	4006
	NW	0	17	52	77	97	110	120	122	123	134	291	462	508	262	0	2347
	Horizontal	0	39	222	447	640	786	880	911	880	786	640	447	222	39	0	6938
	Direct	0	282	651	794	864	901	919	925	919	901	864	794	651	282	0	—
July	N	3	133	109	103	117	126	134	138	134	126	117	103	109	133	3	1621
	NE	8	454	590	540	383	203	144	138	134	126	114	95	71	39	0	3068
	E	7	498	739	782	701	531	294	149	134	126	114	95	71	39	0	4313
	SE	2	248	460	580	617	576	460	291	155	131	114	95	71	39	0	3849
	S	0	39	76	108	190	292	369	395	369	292	190	108	76	39	0	2552
	SW	0	39	71	95	114	131	155	291	460	576	617	580	460	248	2	3849
	W	0	39	71	95	114	126	134	149	294	531	701	782	739	498	7	4313
	NW	0	39	71	95	114	126	134	138	144	203	383	540	590	454	8	3068
	Horizontal	1	115	320	528	702	838	922	949	922	838	702	528	320	115	1	3902
	Direct	7	434	656	762	818	850	866	871	866	850	818	762	656	434	7	—
Oct.	N	0	0	7	40	62	77	87	90	87	77	62	40	7	0	0	453
	NE	0	0	74	178	84	80	87	90	87	87	62	40	7	0	0	869
	E	0	0	163	626	652	505	256	97	87	87	62	40	7	0	0	2578
	SE	0	0	152	680	853	864	770	599	364	137	66	40	7	0	0	4543
	S	0	0	44	321	547	711	813	847	813	711	547	321	44	0	0	5731
	SW	0	0	7	40	66	137	364	599	770	864	853	680	152	0	0	4543
	W	0	0	7	40	62	87	87	97	256	505	652	626	163	0	0	2578
	NW	0	0	7	40	62	87	87	90	87	80	84	178	74	0	0	869
	Horizontal	0	0	14	156	351	509	608	640	608	509	351	156	14	0	0	3917
	Direct	0	0	152	643	811	884	917	927	917	884	811	643	152	0	0	—

The solar heat gain for a building consists of the sum of the transmitted thermal radiation from the sun and of the portion of the absorbed radiation energy that flows indoors.

The solar heat gain coefficient (SGHC) is the portion incident solar radiation that enters through the window's glaze and is expressed as followed.[42]

[41] Heat and mass transfer a practical approach.3rd edition
[42] FINAL REPORT TO THE NATIONAL FENESTRATION RATING COUNCIL FEBRUARY 2006

$$SHGC = \frac{Solar\ heat\ gain\ through\ the\ window}{Solar\ radiation\ incident\ on\ the\ window} = \frac{\dot{q}_{solar,gain}}{\dot{q}_{solar,incident}} = \tau_{sol} + f_i\alpha_{sol}$$

Where $\tau_{sol}$is the overall solar transmittance, α_{sol} is the solar absorptivity of the glass and f_i is the portion of absorbed solar radiation, that is flowing indoors. SHGC ranges from 0 to 1, where 1 corresponds to an opening in the wall with no glazing.
As an example let's calculate the SHGC for a window, that have a total solar gain ($\dot{Q}_{solar,gain}$) of 3000 W and the solar radiation incident on the window is 3068 W/m^2

$$SHGC = \frac{3000}{3068} = 0{,}98$$

The total solar heat gain ($\dot{Q}_{solar,gain} : W$) from a window can be determined on the basis of the SHGC and the windows glazed area[43].

$$\dot{Q}_{Solar,gain} = SHGC \cdot A_{glazing} \cdot \dot{q}_{solar,incident}$$

Let's calculate the total energy obtained by the solar gain ($\dot{Q}_{Solar,gain}$) in a day. For two windows that only have a different solar heat gain coefficient (SHGC:0.87/0.52), an area of 1,2m^2 and when both are facing south in January (based on Fig.23).

Window 1:$\dot{Q}_{solar,gain} = 0.87 \cdot 1.2[m^2] \cdot 5897 \left[\frac{W}{m^2}\right] = 6156.5Wh$

Window 2: $\dot{Q}_{solar,gain} = 0{,}52 \cdot 1{,}2[m^2] \cdot 5897[W/m^2] = 3679.7Wh$

Indirect solar heat gain ($SHGC_{indirect}$) is the gain we get from the windows characteristic absorption of solar radiation and can be determined with ease when we obtained the transmittance and solar heat gain coefficient for the window.[44]

$$f_i\alpha_{sol} = SHGC_{indirect} = SHGC - \tau_{sol}$$

$SHGC_{indirect}$ from a window affects a person in the comfort zone the most when she is not subjected to direct solar transmittance from the window.

To minimize the solar radiation that impacts the window, shading structures can be built or devices can be installed. These will obscure the direct solar radiation from hitting the

[43] Heat and mass transfer a practical approach.3rd edition
[44] FINAL REPORT TO THE NATIONAL FENESTRATION RATING COUNCIL FEBRUARY 2006

whole glazing area of the window and lead to a smaller amount of transmittance through the window, this coefficient is called shading coefficient (SC).[45]

$$SC = \frac{SHGC}{SHGC_{ref}}$$

Where SC is the shading coefficient of the window, SHGC is the "new" solar heat gain factor and the reference SHGC is the "old" solar heat gain coefficient.

A high SC means that the shading effect is smaller. This leads that a larger part of solar radiation will come in through the glazing of the window.

Table 6 Shading coefficient SC and solar transmissivity solar for some common glass types for summer design conditions

Type of Glazing	Nominal Thickness mm	in.	τ_{solar}	SC*
(*a*) Single Glazing				
Clear	3	1/8	0.86	1.0
	6	1/4	0.78	0.95
	10	3/8	0.72	0.92
	13	1/2	0.67	0.88
Heat absorbing	3	1/8	0.64	0.85
	6	1/4	0.46	0.73
	10	3/8	0.33	0.64
	13	1/2	0.24	0.58
(*b*) Double Glazing				
Clear in, clear out	3[a]	1/8	0.71[b]	0.88
	6	1/4	0.61	0.82
Clear in, heat absorbing out[c]	6	1/4	0.36	0.58

*Multiply by 0.87 to obtain SHGC.
[a]The thickness of each pane of glass.
[b]Combined transmittance for assembled unit.
[c]Refers to gray-, bronze-, and green-tinted heat-absorbing float glass.

..

In the table above the SHGC for the reference glazing has been 0.87, if we would like to obtain the SC, for example a 13mm thick heat absorbing window we would do the following calculation.

$$SC = \frac{SHGC}{SHGC_{ref}} = \frac{0{,}505}{0{,}87} = 0{,}58$$

Shading devices that are installed on the exterior can reduce the solar heat gain of windows with up to 80%, where internal devices (e.g. draperies) can reduce thermal load from 5-20%. [46]

[45] Heat and mass transfer a practical approach.3rd edition
[46] Heat and mass transfer a practical approach.3rd edition page

5.2 Comfort zones

Factors influencing the thermal comfort near a window are:

1. Window geometry
2. Room geometry
3. Location of the occupant
4. Glazing system
5. Outside conditions
6. Inside Conditions

These are some of the factors that influences thermal comfort near a window.
The human factor is those factors that are individual and that do not govern the energy flow through the window.

1. Clothing
2. Metabolic rate
3. Location

The human factors are things that can be changed with ease and some of them has been addressed earlier in this thesis.

5.2.1 Windows inside surface temperature

As earlier shown a smaller U-value, leads to a lower amount of energy passing through the window. More drastic are the temperature differences, the window with the higher u-value (1.75) has an inside surface temperature of only 10.9 ° C, where the window whit a low u-value (0.799) has a surface temperature of 16 ° C.

Shown earlier in this thesis (chapter 4), cold surfaces have a great impact on the comfort of a thermal comfort zone. The cool window surface will not only feel cool at contact but will also cool down the surrounding air and lead to draft (fig. 15), which is the most common cause for local thermal discomfort. To reduce the impact of draft on the thermal comfort zone, heaters can be installed under the window to counter the cold air moving down towards the floor (fig. 16).

The U-value is not the only factor that determines the effect of the window (s) in a comfort zone. There is also solar transmittance and emissivity that must be taken in consideration.

The inside temperature of the window is govern by following factors.

1. Glazing
2. Outside conditions (temperature, wind, the sun)
3. Inside conditions (air temperature, surface temperatures, relative humidity, air velocity)

Figure 15. Cold windows effect on the air and causing draft

Figure 16. Heaters effect in front of a window

5.2.2 The View factor

The view factor is a geometrical feature in radiant heat transfer, and is the proportion of radiation which leaves surface 1 and strikes surface 2 as seen in figure 14.[47]

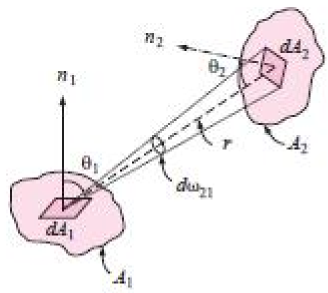


Figure 17. Geometry for the determination of the view factor

The following factors affect the View factors impact on the thermal comfort:

1. Window geometry
2. Room geometry
3. Location of occupant.

As mentioned above the view factor is affected by the windows geometry, room geometry and the location of the receiving surface location (occupant location).
The view factor could be described as, how much the person sees a surface.
It illustrates how much the occupant is influenced by radiant heat exchange of surrounding surfaces. A bigger view factor leads to a larger influence of heat exchange on the person. The view factor is determined by the surfaces geometry and how close the person is to the surface. The closer you are to the window the larger the view factor will be, the same happens if the windows geometry would be bigger.[48]The relation is shown in figure 16.

[47] View factor description
[48] SR_NFRC2006_FinalReport

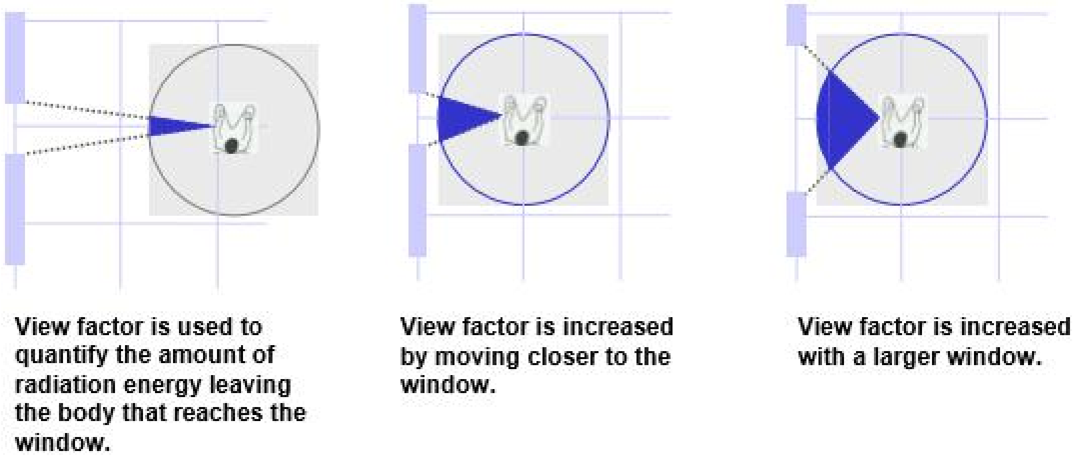


Figure 18. Diagram over the viewfactors effected by geometry

6 FILMS AND SELECTIVE COATINGS

This part of the thesis will deal with window coatings and tints, which can be applied to existing windows. And some manufacturer's products will be used in calculation comparisons. When there is a need to minimize the solar radiation from entering the building and from affecting the thermal comfort zone. And there is no desire or need for external shading devices, window films and selective coating might be the only option to reach the goal of minimizing the solar radiation from affecting the comfort zone.

Solar radiation has a wavelength from 0.3 μm to 3 μm, where nearly half of it is in the visible spectrum (light: 0.4-0.44 μm to 0.63-0.76 μm). The rest of the radiation falls into ultraviolet spectrum (UV: 0.01-0.4 μm) and infrared spectrum (IR: 0.76-100 μm) and thermal energy is brought throughout the spectrum.[49]

The human eye is highly sensitive for stimuli from altering luminous intensity (brightness), therefore the restriction of the visible spectrum could lead to dissatisfaction and even if the thermal comfort would not be affected by this.[50] Window films and selective coating have the capability of reflecting the unwanted solar radiation wave-length from entering the building, the spectrum that is not visible for the human eye and only brings heat. The eye is more sensitive to the green spectrum (0.51-0.57μm) than to UV or IR wavelength's, therefore a window film or selective coating should not absorb or reflect the visible partition of the solar spectrum and let UV and IR in.[51]

The window films and selective coating effect positively on the SHGC and the performance of the window, but can restrict the transmittance of the visible spectrum. Therefore it is a good idea to calculate what the light-to-solar-gain ratio (LSG) is for the glazing system with the window film or selective coating. The LSG determines how much of the visible light is transmitted in ratio of the SHGC, a lower LSG gives a higher transmittance of the visible spectrum and a higher LSG provides a better protection from heating.[52]

$$LSG = \frac{VT}{SHGC}$$

[49] Heat and mass transfer a practical approach.3rd edition
[50] Light-emitting diodes
[51] http://www.giangrandi.ch/optics/eye/eye.shtml
[52] http://www.fsec.ucf.edu/en/consumer/buildings/homes/windows/Tutorial.pdf

Where LSG is the light-to-solar-gain ratio, VT is visible light transmittance through the window and SHGC is the solar-heat-gain coefficient.
To calculate the LSG the only data needed is SHGC (obtained from dealer or manufacturer) and the VT.
As an example calculation:
Window 1: Glazed, clear glass has: VT: 0.79 and SHGC: 0.70.

$$LSG = \frac{0.79}{0.70} = 1.13$$

Window 2: A tinted glass has; VT: 0.45 and SHGC: 0.50. $LSG = \frac{0.45}{0.50} = 0.90$
The result illustrates that even if the tint might have made the SHGC better, it restricts the visible light from entering through the window in comparison to the clear glass.

Due to the eyes ability to sense alterations in brightness, it is important that the selective coating have a good LSG. So that the space gets enough light and does not become dim and is dependent on electric lightning in daytime. Two examples on window films, that have a good effect on the SHGC and have a reasonable LSG are 3M:s Prestige and thinsulate product families.

3 M Prestige product families is a window film product line that provides a high rejection for infrared radiation and high visible light transmission. As seen in the table below most of the films have a LSG near the value of 1 and lets a great partition of the visible light through. These window films work great with low U-values for obtaining a better SHGC and getting a LSG that is desired.

Table 7. Performance & technical data for 3M Prestige family

Product Performance & Technical Data

Glass Type (All 1/4")	Film Type	Visible Light			Total Solar Energy Rejected		Solar Heat Gain Coefficient	U Value	Solar Heat Reduction	UV Light Rejected	Glare Reduction	Visible Light to Solar Heat Gain Ratio
		Reflected (Interior)	Reflected (Exterior)	Transmitted	Normal	60 Degree Angle						
Clear	PR40	7%	7%	39%	60%	66%	0.40	0.99	50%	99.9%	55%	1.0
	PR50	7%	8%	50%	56%	63%	0.44	0.99	46%	99.9%	44%	1.1
	PR60	8%	8%	60%	53%	61%	0.47	0.99	42%	99.9%	32%	1.3
	PR70	9%	9%	69%	50%	59%	0.50	0.99	38%	99.9%	22%	1.4
Tinted	PR40	6%	5%	24%	63%	67%	0.37	0.99	41%	99.9%	55%	0.6
	PR50	6%	6%	30%	61%	66%	0.39	0.99	38%	99.9%	43%	0.8
	PR60	7%	6%	36%	59%	63%	0.41	0.99	34%	99.9%	32%	0.9
	PR70	7%	6%	42%	57%	63%	0.43	0.99	31%	99.9%	22%	1.0
Double Clear	PR40	8%	14%	35%	49%	54%	0.51	0.47	27%	99.9%	55%	0.7
	PR50	9%	15%	45%	47%	53%	0.53	0.47	25%	99.9%	44%	0.8
	PR60	11%	15%	54%	46%	54%	0.54	0.47	22%	99.9%	32%	1.0
	PR70	13%	15%	62%	44%	50%	0.56	0.47	21%	99.9%	22%	1.1
Double Tinted	PR40	8%	8%	21%	61%	64%	0.39	0.47	23%	99.9%	55%	0.5
	PR50	9%	8%	27%	60%	64%	0.40	0.47	22%	99.9%	44%	0.7
	PR60	10%	8%	32%	59%	64%	0.41	0.47	20%	99.9%	32%	0.8
	PR70	12%	8%	37%	59%	62%	0.42	0.47	18%	99.9%	22%	0.9

Window films that have metal coating in the give a great reflecting surface for the radiation to reflect from, but at the cost of building a Faraday cage and blocking data signals from entering or leaving the building.[53][54] That's why 3M prestige family is not metalized, so they would not cause signal interference nor corrosion.[55]

3M Thinsulate window films has closely to non-reflection and is almost an invisible film, this makes it extremely good for historical buildings which façades would be ruined by reflecting films.[56] And are also suitable for newer buildings windows to improve the SHGC and still obtain a good LSG and the facades original look. In the table below shown the new specifications the old windows got from the Thinsulate window films, which are almost comparable with modern windows.

[53] https://en.wikipedia.org/wiki/Faraday_cage
[54] http://yle.fi/uutiset/kannykkapuhelu_voi_pysahtya_ikkunaan/6229407
[55] http://multimedia.3m.com/mws/media/958839O/3mtm-window-film-prestige-family-card.pdf?fn=Prestige%20Family%20Card_98-0150-036

[56] http://multimedia.3m.com/mws/media/1149166O/3m-thinsulate-window-film-case-study-gov-retail-banks.pdf?fn=RED-CaseStudy_MNGov_98-0150-0811

Table 8. Performance & technical data of 3M thinsulate family

Product Performance and Technical Data

Glass Type (All 1/4")	Film Type	Visible Light			Total Solar Energy Rejected	Solar Heat Gain Coefficient (G Value)	U Value		Heat Loss Reduction	Heat Gain Reduction	UV Light Rejected	Glare Reduction	Visible Light to Solar Heat Gain Ratio
		Reflected (interior)	Reflected (exterior)	Transmitted			btu/ hft²F	w/ m²K					
Clear	Thinsulate™ 75	12%	16%	74%	47%	0.53	0.63	3.6	40%	35%	99.9%	17%	1.4
Tinted	Thinsulate™ 75	10%	8%	44%	60%	0.40	0.63	3.6	40%	37%	99.9%	17%	1.1
Double Clear	Thinsulate™ 75	17%	21%	66%	49%	0.51	0.35	2.0	26%	27%	99.9%	16%	1.3
Tinted Clear	Thinsulate™ 75	15%	10%	40%	63%	0.37	0.35	2.0	26%	27%	99.9%	15%	1.1

For comparison of these two films, to the performance of a window without any film, a calculation of total solar heat gained and LSG can be made. The window without film is the reference window ($\text{window}_{reference}$) and is a clear double glass window, has an area of 1 m^2 a U-value of 2.0, the SHGC is 0.70 and a VT of 0.79.[57] Window $_{prestige}$ has a clear 3M PR40 film installed, and has a U-value of 2.00, a SHGC of 0.40 and a VT of 0.39 (table 6). A clear 3M thinsulate 75 film is installed onto window $_{thinsulate}$ giving the window, a U-value of 2.0 a SHGC of 0.53 and a VT of 0.74 (table 7). The total solar radiation incident is taken from table 4, in April and from the east direction, giving a total solar radiation incident of 4006 W/m^2.

Window $_{reference}$: $\dot{Q}_{solar,gain} = 0.70 \cdot 1 \cdot 4006$ = 2804 Wh

Window $_{prestige}$: $\dot{Q}_{solar,gain} = 0.40 \cdot 1 \cdot 4006$ = 1602 Wh

Window $_{thinsulate}$: $\dot{Q}_{solar,gain} = 0.53 \cdot 1 \cdot 4006$ = 2123 Wh

As the calculation shows the total solar heat gained from the reference window is much higher than the windows with films. The prestige film has a 43% smaller solar heat gain, compared with the reference window. The installation of a thinsulate film gives a 24% smaller solar heat gain than the reference window,

[57] http://www.commercialwindows.org/vt.php

To calculate how much visible light is transmitted into the room in relation of SHGC, we calculate the LSG for each window.

$\text{Window}_{\text{reference}} : LSG = \frac{0.79}{0.7} = 1.13$

$\text{Window}_{\text{prestige}} : LSG = \frac{0.39}{0.4} = 0.98$

$\text{Window}_{\text{thinsulate}} : LSG = \frac{0.74}{0.53} = 1.4$

The calculation of LSG shows that the window with 3M prestige film, the visible spectrum is more affected by the lower SHGC, in comparison with the 3M thinsulate film. The thinsulate film has the best visible light to SHGC ratio and performs much better than the reference window regarding the LSG and transmitted solar energy.

7 DISCUSSION

In this work we have gone through heat transfer and the different transit modes thermal energy utilizes when it strives to reach thermal equilibrium. How Windows and its glazing properties affect and control the thermal loads that are put upon them.

The windows impact on thermal comfort is very dependent on the properties the window has. When the outside temperatures are lower than the comfortable temperature inside we can maintain the correct temperature better if we use double or triple pane windows that have a better U-value (u-factor) than older double pane windows. We can also choose windows with a greater thermal resistant medium, such as krypton (g) or even vacuum, instead of adding more glass panes to maximize the thermal resistance. By choosing a window with vacuum we eliminate the conductive heat transfer through the window glaze, leaving only thermal radiation that passes through the medium. The frames will still be working as thermal conductors, this is still a smaller area with lower temperatures on the inside of the window assembly. Giving a much smaller area where convective cooling could occur, it is minimizing the amount of cold air moving downwards and counteracts the formation of draft.

To regulate the thermal radiation for entering the comfort zone the U-value does not add any resistance. To minimize the unwanted thermal radiation for entering the building, we need to address the SHG of the window. The SHGC of a window tells us how much thermal energy will be coming through the glazing and we have the possibility to affect the solar radiation that hits the glazing. With internal or external shading devices we can affect the shading coefficient (SC), in other words we can interrupt the incident solar radiation that would hit the window.

Internal shading such as blinds and drapers are an easy way to restrict the heat gain, by altering their positions we block or let the radiation in. Internal shading devices properties of minimize the heat gain is dependent on the material of the shading devices, such as emissivity, draperies and blinds reflect the incoming solar radiation back towards the window.

In cooler countries where solar heat gain (SHG) is wished to be obtained, during winter periods, windows with low U-value and selective coating, could be installed instead for permanent fixtures. The filters would only let the spectrums long-wave infrared and the visible parts of the spectrum enter the building.[58] This is done by using low-emissive coating and allows more of the solar spectrum to enter the building, and still reflect back the thermal long-wave radiation that is emitted from inside.

If we do not want heat gains throughout the year, especially during the warmer periods, shading devices might be a good idea for restricting the SHG during this period. As internal shading, drapers are more versatile, because during colder periods drapes reduce heat loss by forming an almost stagnate air space in front of the window minimizing the total U-value of the window. Exterior shading devices might be handy during warmer periods, but during the colder periods they might obscure solar radiation from entering the building. Therefore natural shading devices, such as leaf trees could work as an effective solution for residential houses. For bigger complexes retractable shading devices could also help to obscure solar radiation during the warm periods and be retracted during periods when the heat load is wanted.

In warmer climates τ_{sol} affects comfort more than what a high U-value would do. The solar radiation, diffuse and incident is the biggest reason for heat gains through windows. With spectral selective coating, that filters all solar radiation wavelengths except the visible spectrum, we can restrict the radiation from heating up the space. This coating will not allow the long-wave radiation from the interior to pass through the window,

[58] http://www.commercialwindows.org/primer_intro.php

but as earlier stated increasing the air velocity in the zone will cool down the radiant temperature.

Tints and coatings that reflect thermal radiation from the sun should be installed on the outer glass panes inner surface, to maximize the gain from them. By this mean the thermal radiation is emitted away from the window.

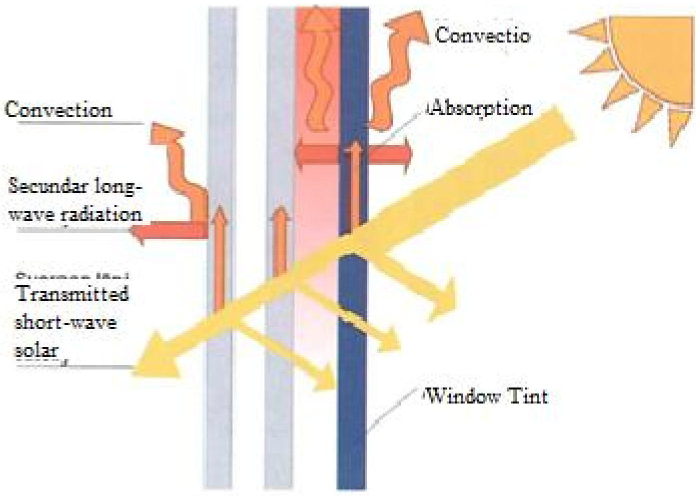


Figure 19. Diagram over solar radiation with the tint/coating installed on the outer pane of a triple pan window.

If the tints are installed on the outer side of the inner glass pan, heat would be absorbed inside the window and the window's heat load would get greater and emit more long waved thermal radiation into the comfort zone.

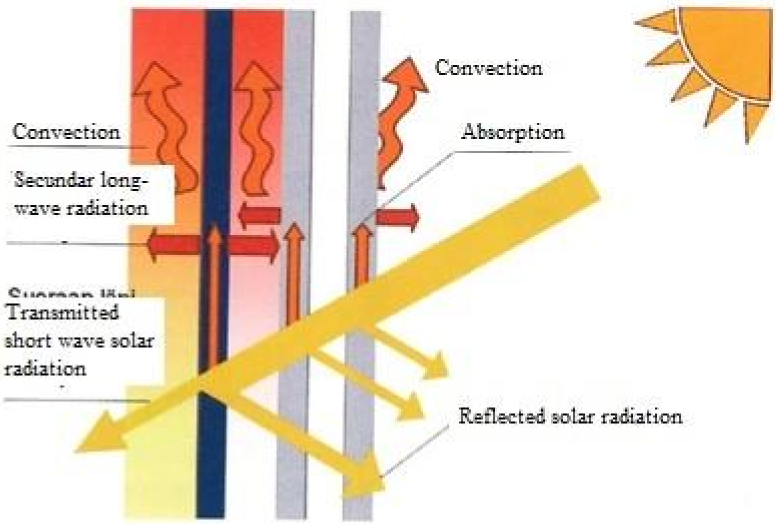


Figure 20. Diagram over heat building up in the window, if the tint/coating is installed on the inner pane of the window.

The prime function of tints and selective coating is to make the windows SC better, this means that not so much radiation enter the zone and surfaces in the comfort zone does not gain heat from radiation from outside.

By choosing windows that have a low U-value, low-emissivity and installing selective coating/tints onto the window to get a lower SC we can minimize effectively the outer climate from interacting with our inside comfort climate. Then we have the option of exterior shading devices that can be installed or planted, for a far lower exposure of incident solar radiation.

When trying to summarize how a window affects the comfort zone, we need to take in concern which climate is more dominant. Is it long cold and dark periods like in the northern parts of the globe or is the climate warmer with more solar exposure?

Areas with more solar exposure, the solar heat gain is key factor when we determine the windows impact on a comfort zone. And in areas where solar exposure is not as frequent, the U-value is during the colder periods the key factor that effects the windows impact on the comfort zone. But during the warmer periods the sun might not even go down at all, this makes SHGC the key factor that determines how the window affects the thermal comfort.

There are dynamic selective coatings for windows and they are in great use in the automotive industry, in rearview mirrors and active dimmers in the airline industry (Boeing 787 Dreamliner)[59].

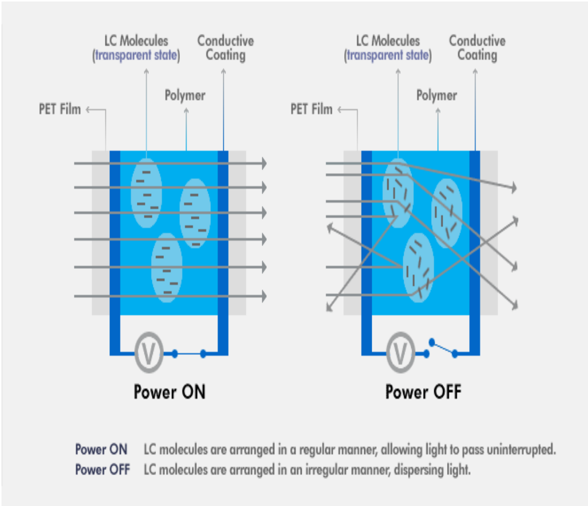


Figure 21. How "smart glass" works

These photovoltaic active windows can adapt with the solar radiation intensity and if needed the occupant would "dim" the window using a mobile app.[60]

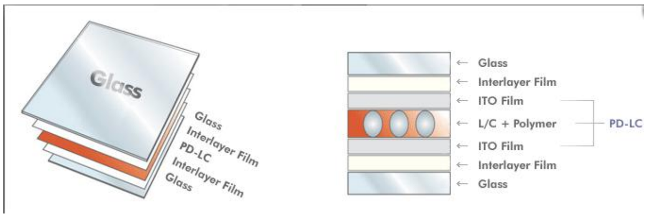


Figure 22. Structure of smart glass.

I think that thermal comfort would see a great benefit from these dimmable windows and tints have to offer. By actively changing the character of the glazing e.g. buildings in the northern part of the globe could get the wanted solar heat gain when needed and during warmer periods the transmittance of solar radiation would be restricted. The LSG would from time to time be effected, by limitations for VT these dimmable windows could form.

[59] http://www.boeing.com/commercial/aeromagazine/articles/qtr_4_06/article_04_4.html 16.5.2016
[60] http://www.digitaltrends.com/home/smart-windows-dim-smartphone/ 16.5.2016

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42. CBE, WINDOW REPORT FOR HUMAN THERMAL COMFORT, FINAL REPORT TO THE NATIONAL FENESTRATION RATING COUNCIL, 2006 page 54
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44. “Because Tsol and SHGC are easily obtained values for window products, we can easily determine the quantiy NA by the following: NA = SHGCindirect = SHGC – Tsol” CBE, WINDOW REPORT FOR HUMAN THERMAL COMFORT, FINAL REPORT TO THE NATIONAL FENESTRATION RATING COUNCIL, 2006 page 55
45. Heat and mass transfer a practical approach.3rd edition page 592
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47. Heat and mass transfer a practical approach.3rd edition page 606
48. CBE, WINDOW REPORT FOR HUMAN THERMAL COMFORT, FINAL REPORT TO THE NATIONAL FENESTRATION RATING COUNCIL, 2006 page 32
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FIG.1	Roy Karanen
FIG. 2	(Heat and mass transfer a practical approach 3rd edition. /Cengel//page 26 figure 1-31)
FIG.3	Roy Karanen
FIG.4	Heat and mass transfer a practical approach 3rd edition. /Cengel//page 588 figure 11-42
FIG.5	(http://hyperphysics.phy-astr.gsu.edu/hbase/thermo/thereq.html)
FIG.6	Roy Karanen
FIG.7	ISO 7730-2005/ANNEX G
FIG.8	ISO 7730-2005
FIG.9	ANSI/ASHRAE Standard 55-2004
FIG.10	Roy Karanen
FIG.11	Roy Karanen (obtained by using DOF-lämpö)
FIG.12	Thermal image of a window; note the excess heat loss at the bottom (Roy Karanen)
FIG.13	Heat and mass transfer a practical approach, 3rd edition/figure 11-4/page. 592
Fig. 14	Heat and mass transfer a practical approach, 3rd edition/figure 11-33/page. 584
FIG.15	Rakennusten sisäilmasto ja LVI-tekniikka/Olli Seppänen/Matti Seppänen/page.22/2:14
FIG.16	Rakennusten sisäilmasto ja LVI-tekniikka/Olli Seppänen/Matti Seppänen/page.22/2:14
FIG.17	Heat and mass transfer a practical approach, 3rd edition/figure 12-2/page. 606
	CBE, Window report for human thermal comfort,
FIG.18	Final report to the National fenestration rating council, 2006, figure :20, page 33

FIG.19 Aurinkosuojaus, Rehva ohjekirja No 12, 2011, page. 19

FIG.20 Aurinkosuojaus, Rehva ohjekirja No 12, 2011, page. 20

FIG.21 (http://www.glass-apps.com/products/smart-glass-windows/ .16.5.2016)

FIG. 22 (http://www.glass-apps.com/products/smart-glass-windows/ 16.5.2016)

Table 1: ISO 7730/2005/ANNEX B

Table 2: ISO 7730-2005 – ANEX C

Table 3: Humidex chart. http://www.accuracyproject.org/heatindexchart.html (31.5.2016)

Table 4: Surafce temperatures for windows based on u-value 0.799 and 1.75

Table 5: Hourly variation of solar radiation incident on various surfaces and the daily totals throughout the year at 40° latitude / ASHRAE Handbook of Fundamentals, Ref. 1, Chap. 27, Table 15.

Table 6: Shading coefficient SC and solar transmissivity solar for some common glass types for summer design conditions/ ASHRAE Handbook of fundamentals. chap. 27, table11.

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Table 8: http://multimedia.3m.com/mws/media/1174843O/3m-thinsulate-window-film-sample-film-holder.pdf?fn=Climate_Control_Family_Card_98-0

APPENDICES

Annex B
(informative)

Metabolic rates of different activities

Further information on metabolic rates is given in ISO 8996. That elderly people often have a lower average activity than younger people also needs to be taken into account.

Table B.1 — Metabolic rates

Activity	Metabolic rate	
	W/m^2	met
Reclining	46	0,8
Seated, relaxed	58	1,0
Sedentary activity (office, dwelling, school, laboratory)	70	1,2
Standing, light activity (shopping, laboratory, light industry)	93	1,6
Standing, medium activity (shop assistant, domestic work, machine work)	116	2,0
Walking on level ground:		
2 km/h	110	1,9
3 km/h	140	2,4
4 km/h	165	2,8
5 km/h	200	3,4

Annex F
(informative)

Humidity

Humidity can be expressed as relative or absolute humidity (see ISO 7726). It is the absolute humidity expressed as water vapour pressure in the air, which influences the evaporative heat loss from a person. This influences the general thermal comfort of the body (heat balance). At moderate temperatures (< 26 °C) and moderate activity levels (< 2 met) this influence is, however, rather limited. In moderate environments, the air humidity has only a modest impact on the thermal sensation. Typically a 10 % higher relative humidity is felt to be as warm as a 0,3 °C rise in the operative temperature. For higher temperatures and activities, the influence is greater. Under transient conditions, the humidity can also have a significant influence.

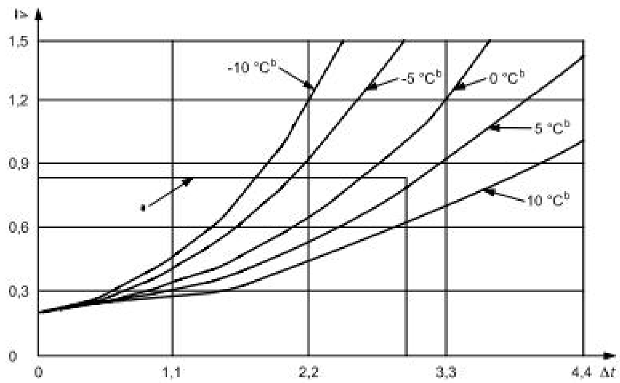
If humidity limits are based on the maintenance of acceptable thermal conditions based solely on comfort considerations — including thermal sensation, skin wetness, skin dryness, and eye irritation — a wide range of humidity is acceptable.

Annex G
(informative)

Air velocity

The air velocity in a space influences the convective heat exchange between a person and the environment. This influences the general thermal comfort of the body (heat loss) expressed by the PMV-PPD index (see Clauses 4 and 5) and the local thermal discomfort due to draught (Clause 6). There is no minimum air velocity that is necessary for thermal comfort. However, increased air velocity can be used to offset the warmth sensation caused by increased temperature.

Often, the air velocity is increased by opening of windows or use of fans to adapt to warmer environments. Under summer conditions, the temperature can be increased above the level allowed for comfort if a means is provided to also elevate the air velocity. The amount by which the temperature may be increased is shown in Figure G.1. The combinations of air velocity and temperature defined by the lines in this figure result in the same total heat transfer from the skin. The reference point for these curves is 26 °C and 0,20 m/s of air velocity. The benefits that can be gained by increasing air velocity depend on clothing, activity, and the difference between the surface temperature of the clothing/skin and the air temperature. Figure G.1 shows the air velocity that is required for typical summer clothing (0,5 clo) and sedentary activities (1,2 met) that correspond to summer comfort.



For light primarily sedentary activity, Δt should be < 3 °C and $\bar{v}$ < 0,82 m/s.

Key

Δt temperature rise above 26 °C

$\bar{v}$ mean air velocity, m/s

[a] Limits for light, primarily sedentary, activity.

[b] $(\bar{t}_r - t_a)$, °C (t_a, air temperature, °C; $\bar{t}_r$, mean radiant temperature, °C).

Figure G.1 — Air velocity required to offset increased temperature

Figure G.1 applies to an increase of temperature above 26 °C with both t_r and t_a increasing equally. When the mean radiant temperature is low and the air temperature is high, elevated air velocity is less effective at increasing heat loss. Conversely, elevated air velocity is more effective at increasing heat loss when the mean radiant temperature is high and the air temperature is low. Thus, the curve in Figure G.1 that corresponds to the relative difference between air temperature and mean radiant temperature must be used. Large individual differences exist between people with regard to the preferred air velocity. Therefore, the elevated air velocity must be under the direct control of the affected occupants and adjustable in steps no greater than 0,15 m/s.