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Computational code development for parameterized study in the calculation of the thermal load in a refrigerating chamber

Desenvolvimento de um código computacional para estudo parametrizado no cálculo da carga térmica em uma câmara frigorífica

Desarrollo de un código computacional para parámetros de estudio en el cálculo de carga térmica en una cámara frigorífica

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Abstract

Cold rooms are fundamental equipment for the preservation of perishable foods, guaranteeing the maintenance of the quality of products in the stages of their processing and distribution. The correct dimensioning of this equipment represents efficiency related to the cooling and freezing performance, as well as the energy efficiency of the system. This project deals with the development of a computational code on the EES platform (Engineering Equation Solver) to determine the energy consumption of the evaporator unit (thermal load) of a cold room. The study presents parameterized results for the thickness of the thermal insulation and the inlet temperature of the products. It was verified that the discrepancy between the maximum and minimum operation regimes of the cold room, represents a reduction of approximately 20,19% of the energy consumption of the evaporator unit. Thus, it can be concluded that the parameterized study can result in a diagnosis of energy savings for cold storage projects.

Keywords: Industrial refrigeration; Thermal load; Refrigerating chamber; Parametric study.

Resumo

As câmaras frigorificas são equipamentos fundamentais para a conservação de alimentos perecíveis, garantindo a manutenção da qualidade dos produtos nas etapas do seu processamento e distribuição. O dimensionamento correto desse equipamento representa eficiência energética relacionada ao desempenho do resfriamento e congelamento. Este trabalho trata do desenvolvimento de um código computacional na plataforma EES (Engineering Equation Solver) para o estudo parametrizado aplicado a espessura do isolante térmico e a temperatura de entrada dos produtos alimentícios. O estudo parametrizado busca diagnosticar o melhor ponto de operação do ponto de vista da potência requerida pela unidade evaporadora da câmara. Foi verificado que a discrepância entre os regimes de máxima e mínima operação da câmara, representa uma redução de aproximadamente 20.19% do consumo energético da unidade evaporadora. Dessa forma, conclui-se que o estudo parametrizado pode resultar em diagnóstico de economia de energia para projetos de câmara frigorífica.

Palavras-chave: Refrigeração industrial; Carga térmica; Câmara frigorífica; Estudo paramétrico.

Resumen

Las cámaras frigoríficas son equipos esenciales para la conservación de alimentos perecederos, asegurando el mantenimiento de la calidad del producto en las etapas de procesamiento y distribución. El tamaño correcto de este equipo representa la eficiencia energética relacionada con el rendimiento de enfriamiento y congelación. Este trabajo trata del desarrollo de un código computacional en la plataforma EES (Engineering Equation Solver) para el estudio parametrizado aplicado al espesor del aislante térmico y la temperatura de entrada de los productos alimenticios. El estudio parametrizado busca diagnosticar el mejor punto de funcionamiento desde el punto de vista de la potencia requerida por la unidad evaporadora de la cámara. Se encontró que la discrepancia entre los regímenes de operación máximo y mínimo de la cámara representa una reducción de aproximadamente 20.19% en el consumo de energía de la unidad evaporadora. Así, se concluye que el estudio parametrizado puede resultar en un diagnóstico de ahorro energético para proyectos de almacenamiento en frío.

Palabras clave: Refrigeración industrial; Carga térmica; Cámara de refrigeración; Estudio paramétrico.

1. Introduction

Ever since the beginning of time, man has yearned for two basic needs: to live in comfortable housing and to store foods for long periods. It was already known that cooler places in the interior of a cave could extend food conservation. Only in 1756, Dr. William Cullen demonstrated artificial refrigeration in his experiment lowering the pressure of a container of ether, which then boiled, absorbing heat from surroundings, and creating a small amount of ice.

Since then, many others refrigeration systems and fluids have been used, and the vapor compression cycle has become the most widely used. Such systems have four basic components: a compressor, a condenser, a thermal expansion valve, and an evaporator. A circulating refrigerant undergoes phase changes removing heat from the spaces to be cooled to outside at higher temperatures. (Barbosa, 2020).

Depending on the application, the refrigeration systems can be distinguished from the range of temperature use: above 15°C, comfort conditioning; from -70°C to 15°C, industrial refrigeration; and below -70°C, the cryogenics refrigeration. The present work focuses on industrial refrigeration which can be applied to, among many others areas, the processing and storage food industry (meat, fish, beverage, milk products). (Stoecker, 2018).

The technological advances in the cooling industry have allowed that food in general, especially perishable foods, could be stored and transported for longer-term, maintaining nutritional and sensory qualities (Souza, 2013). The storage temperature plays an important role in the storage of fresh foods ensuring the safety, quality, and profitability of the whole process of refrigeration through cooling chambers. (Ferreira, 2019).

In the last years, refrigeration usage has been increased substantially particularly driven by the growth of the global market of commodities, the fresh food industry, and the internet economy (Kearney et al., 2019). Within the food supply chain, the refrigeration process emerges as one of the biggest energy consumers and is responsible for approximately 35% of all electricity consumed in the food industry (Li et al., 2017). Moreover, energy consumption costs related to food storage under refrigeration demands special concern (Jiang et al., 2020).

The continuous and increasing demand for materials in the current world's economic development can lead to a possible energy shortage in the future (Bin Hu et al., 2018). Thus, a careful study in designing cooling chambers must be mandatory to find out the optimal energy consumption. According to Camioto (2016), adopting measures that guarantee the efficient use of energy in the development and execution of projects are all good environmental and financial practices.

When defining the thermal conditions for cooling chambers, workers' health and food quality are some concerns that must take into account besides economic and environmental aspects. Unpleasant environmental conditions caused by the thermal load may lead to low worker productivity and an increase in energy consumption. (Cunha et al., 2013).

The design of cooling chambers for food must take into account the controlling of thermo-hygrometrics conditions. The entrance temperature of products plays an important role in preserving food quality which must be precooled to a suitable temperature before being stored, especially perishable commodities (Franco, 2017). Therefore, this parameter is of particular importance in the refrigeration industry and must take into account economic, environmental, health work conditions, and food conservation aspects.

Within this context, the present work aims to develop a computational code based on the EES software (Engineer

Equation Solver) to find the thermal load required by the evaporator unit in a cooling chamber. The EES plays an important role in the entire procedure of calculations providing, among many other features, an extensive thermodynamic properties database for refrigerant fluids and a linear and non-linear solver for algebraic equations. Furthermore, the work also presents a parametric study over some important variables guiding it to the most efficient conditions of the refrigeration operation. Oliveira's case study (2001) serves as a base for computational code implementation.

2. Methodology

2.1 Project Principles

This work uses a case study as a methodological approach with a predominance of qualitative data (Cauchick-Miguel et al., 2017; Pereira et al., 2018). Deals with the design of a cooling chamber located in Belém city, PA, Brazil. The city location is arbitrary and could be any other demanding a similar storage flow. According to INPE, the national agency responsible for the weather forecast in Brazil, in November, the highest temperature and relative humidity recorded were: 32.4°C and 70%, respectively.

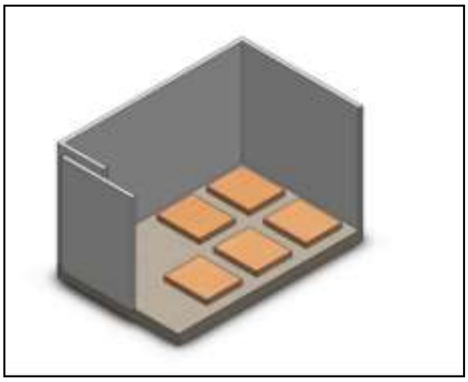
The highest temperature recorded in the last decade in Belém City, according to the INMET, (2015) was 37°C in December 2015. However, it was considered unusual and, then the value of 32.4°C was taken as a representative temperature for the chosen location. Besides, this temperature is considered a conservative parameter since, in general, refrigeration facilities for storage are built inside not air-conditioned sheds.

The cooling chambers were designed for a dairy demand of 10ton (22046.43 lb) for pork meat and 5ton (11023.11 lb) for apples and both must be in temperature and humidity-controlled environments of -5°C, 87%, and 0°C, 92%, respectively. The commodities thermal properties were selected from the storage practices indicated for pork meat, ABSC (2014), and for apples, Vieira (2019).

2.2 Chambers Dimensions

From the mass product flow and its density (the mass per storage space ratio) as indicated by ASHRAE (2010), the cooling chamber model for apples is shown in Figure 1.

Figure 1 – 3D model for apples storage.

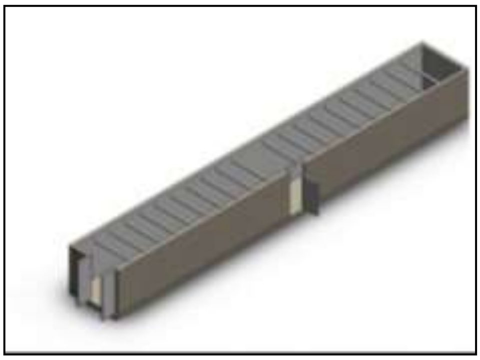


Source: Authors.

Figure 1 shows the distribution of the 5 apple cartons storage pallets inside the chaber which has 3.2 m wide, 5 m long, and 3 m high. The sidewall and the top of the chamber were suppressed for visualization purposes.

In Figure 2, the storage chamber for pork meat is shown and its dimensions were obtained in an analogous way as for apples.

Figure 2 – 3D model for pork meat storage.



Source: Authors.

Looking at the pork storage chamber it is possible to see the brackets for hanging the meat that is chilled inside the chamber which has 3.2 m wide, 27.06 m long, and 3 m high, the last is indicated by ABSC (2014). Masonry walls were applied to increase its mechanical strength and, therefore, to support the product weight.

The length of the chamber is eight times larger than its width due to the way the products are moved in and out from rack arrangements in warehouses.

2.3 Input Data

Table 1 lists the input data to calculate the thermal load. The index (m) and (c) are applied to the apple and fresh pork chamber storage, respectively. The other parameters are used for both situations.

Table 1 – Input data for thermal load calculations.

Parameters [units]	Data
U (roof) [W/m².°C]	0.166
U (m), (walls) [W/ m².°C]	0.166
U (floor) [W/ m².°C]	0.184
U (c), (walls) [W/ m².°C]	0.156
k (PUR) [W/m.°C]	0.021
k (EPS) [W/m.°C]	0.033
A (m), (roof and floor) [m²]	65.20
A (m), (floor) [m²]	16.00
A (c), (walls) [m²]	262.19
A (c), (roof) [m²]	86.70
A (c), (floor) [m²]	86.70
Np (m), dimensionless	2
Np (c), dimensionless	4
C_e (m), (cooling) [kJ/kg.°C]	3.87
C_e (c), (cooling) [kJ/kg.°C]	3.08
C_e (c), (freezing) [kJ/kg.°C]	3.10
hc [kJ/kg]	166.00
T_e, (m) (in) [°C]	10.0
T_e, (c) (in) [°C]	5.0
T_r (m), [h]	8
T_r (c), [h]	10
Q (m), [kW]	42.550
Q (c), [kW]	41.440
D_t (m), dimensionless	0.0020
D_t (c), dimensionless	0.0022
D_{to} (m), dimensionless	0.1250
D_{to} (c), dimensionless	0.1670
D_f dimensionless	0.8000
E dimensionless	0.9000
Q_{eq} [W/person]	272.00
W_i [W/ m²]	10.00

Source: Authors.

The data found in Table 1 is used in the computational code to develop both refrigerating chambers. Values came from project premise or technical tables available in the literature.

2.4 Thermal Load Calculation

The calculation of the thermal load becomes necessary to determine the required refrigeration power for the chambers. Equations 1 to 6 follow the methodology presented in ASHRAE (2010).

The convection-conduction rate of heat transfer through the walls and roof is given by Equation (1). Solar thermal radiation can be neglected since the chamber are located inside the shed.

$$Q_c = UA(T_e - T_i) \tag{1}$$

Thermal conductivity data for U calculation were obtained from Ananda (2020), a local thermal insulation provider. Equations 2 and 3 give the product cooling power required to reach a constant heat transfer rate without phase change (sensible heat) and with phase change (latent heat), respectively. The latter is applied only for pork meat. We are considering a constant specific heat capacity coefficient.

$$Q_p = C_e M \frac{T_e - T_i}{T_r} \tag{2}$$

$$Q_{ph} = \frac{Mh}{T_r} \tag{3}$$

Equations 4 to 6 define the thermal load related to external air infiltration, the heat dissipated by persons, and illumination, ASHRAE (2010), respectively.

$$Q_{if} = QD_t D_f (1 - E) \tag{4}$$

$$Q_o = N_p Q_{eq} D_{to} \tag{5}$$

$$Q_i = W_i A_{pi} D_{to} \tag{6}$$

The thermal load of product packages should only be taken into account if the quantity of material exceeds 10% of the gross weight of the products, ASHRAE (2010). In the present case study, apples are packed in cardboard boxes and the pork meat is hung which represents less than the minimum indicated in ASHRAE, and then, the calculation was ignored.

Based on the EES platform, all the presented equations, as well as the parameters listed in Table (1), were implemented in a computer program to validated Oliveira's (2021) case study. In the present work, an analysis has been made to find the values of the parameters which led to the minimum power consumption in the evaporator unit used for the chamber refrigeration.

2.5 Thickness Insulation and Entrance Temperature of the Products

A parametric study of the effect of thermal insulation thickness over the thermal load products was conducted. The variation range from 0.05m to 0.15m was considered and is indicated by ABCS (2014) for cooling chambers working near to 0°C. Two of the most widely thermal insulation materials applied to build cooling chambers were considered: the Rigid Polyurethane Foam (RPF) and the Expanded Polystyrene (EPS), ABCS (2014).

The entrance temperature was considered in another parametric study to show how the precooling process impacts the thermal load calculations.

The entrance temperature range for pork meat goes from 2.5°C to 7.5°C, as indicated by ABCS (2014). For apples, it was considered the range from 5°C to 15°C, Vieira (2019). Both ranges could keep the quality of all products.

3. Results and Discussion

Tables 2 and 3 list the thermal load calculations of the cooling chambers for apples and pork meat, respectively. Portions of the total thermal load for both situations are described. Initially, the thermal load was calculated based on Oliveira's (2021) data work. Those values are listed in Table (1). For the validation of the model, the computer program developed in the present work gave similar results to those from Oliveira (2021) using the RPF as thermal insulation with 0.1 m thick.

Table 2 – Thermal load results of the cooling storage for apples.

Thermal load	Power [kW]
Conduction	0.387
Product	6.719
Air infiltration	0.007
Occupation	0.068
Illumination	0.020
Total	7.201

Source: Authors.

Table 3 – Thermal load results of the cooling storage for fresh pork.

Thermal load	Power [kW]
Conduction	2.195
Product	55.09
Air infiltration	0.015
Occupation	0.201
Illumination	0.144
Total	57.645

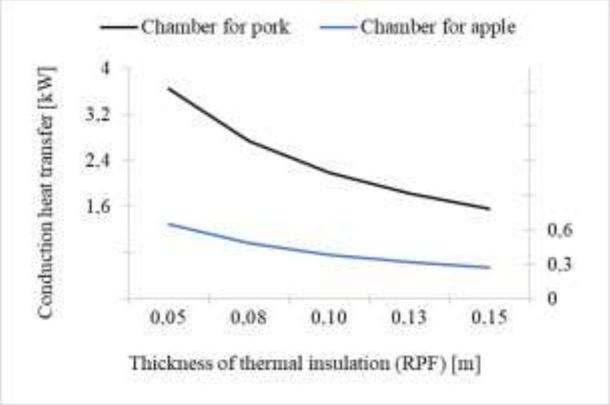
Source: Authors.

Table 2 shows data approximately, 93% of the total termal load for the apples chamber is due to the product itself, while the pork meat representes 95% of the termal load for its chamber. The second highest values are related to the thermal load of conduction which represents 5.38% and 3.81% of the total thermal load for apples and fresh pork, respectively.

3.1 Analysis of the Thermal Insulation Thickness Using PUR

Figure 3 shows the parametric results for the thermal insulation thickness variation applied to the walls and the roof. The thermal loads of conduction are compared for both the products using the RPF thermal insulation material which goes from 0.05m to 0.15m.

Figure 3 –Conduction heat transfer variation using PRF.



Source: Authors.

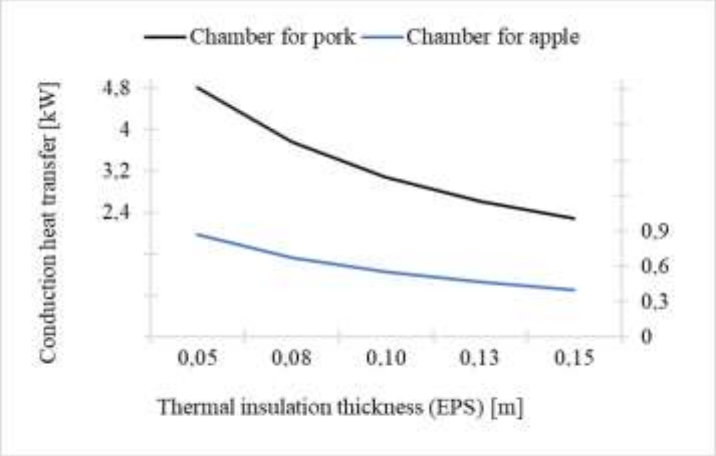
In Figure 3, it can be noticed that the conduction heat transfer rate decreases as the thickness of thermal insulation increases. The scenario that leads to a minimum conduction thermal load represents a reduction of 57.8% (0.377kW) and 56.9% (2.07kW), for apples and fresh pork, respectively when compared to the maximum scenario. Thus, the conduction thermal load of fresh pork is 5.5 times greater than the thermal load of apples. It's explained by the fact of: a) the contact surface area for fresh pork is roughly 4.4 times and b) the cooling temperature is 5°C lower when compared to the apples.

Also in the graph the plot curves decrease rapidly for small values of thickness of insulation and tend to become constant for larges values. It indicates that excessive use of insulation material does not correspond to any significant increase of the thermal resistance for conduction (Çengel, 2012). Similar results were obtained in Passos's (2018) work.

3.2 Analysis of the Thermal Insulation Thickness Using EPS

An analogous analysis was performed using the Expanded Polystyrene (EPS) varying the insulation thickness using another material. Results can be seen in Figure 4.

Figure 4 – Conduction heat transfer rate through walls and roof using EPS insulation material.



Source: Authors.

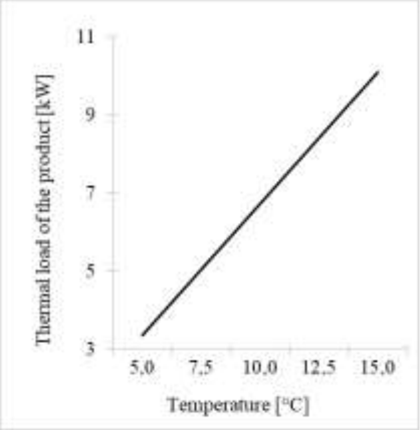
In Figure 4, the results using EPS insulation are quite similar to those using RPF. When comparing the maximum and minimum values for conduction thermal load, a reduction of 53.87% (0.47kW) and 57.72% (2.54kW) can be estimated for apples and fresh pork, respectively, as a consequence of the insulation thickness increase.

From Figures 3 and 4, the analysis of the heat conduction rate, for an average thickness of 0.1m, shows that the RPF insulation properties lead to the lowest heat loss which corresponds to 71% of the heat conduction when using the EPS.

3.3 Entrance Temperature Analysis for Apples

Figure 5 shows how the thermal load of the product varies as a function of the entrance temperature of apples.

Figure 5 – Thermal load of the product as a function of the entrance temperature.



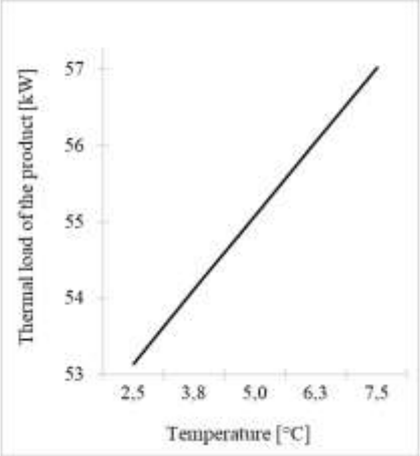
Source: Authors.

Figure 5 shows that the thermal load of the product can be reduced to 66.67% (6.71kW) if the entrance temperature is only 10°C lower. According to Vieira (2019), the correct entrance temperature of products reduces the evaporating unit power demand and keeps its quality.

3.4 Entrance Temperature Analysis for Pork Meat

Figure 6 shows how the thermal load of the products varies as a function of the entrance temperature for pork meat.

Figure 6 – Thermal load of the product as a function of the entrance temperature.



Source: Authors.

It can be verified in the Figure 6 that the thermal load of the product can be reduced to 5.71% (4.27kW) if the entrance temperature is only 10°C lower.

3.5 Comparative Analysis Between the Entrance Temperature and the Cooling Chamber Operation Cost

Apples must be precooled in cold water immediately after they are harvested (Vieira, 2019) and, in the same sense, pork meat also needs precooling (ABCS, 2014) to guarantee their qualities during storage.

The parametric analysis presented here shows how significant the precooling process and consequently, the entrance temperature, affects the total thermal load which can be reduced up to 10.98kW.

3.6 Overall Understanding of the Thermal Load of Cooling Chambers

The calculations of the steady portion contributions of the thermal loads (infiltration, occupation, illumination) and those determined by the parametric study such as conduction and product thermal loads were responsible for the understanding of the refrigeration power consumed by the cooling chambers. Overall results are presented in Table 4 considering minimum, average and maximum power consumption operations regimes.

Table 4 – Thermal load for different cooling chambers operation regimes.

Operation regimes	Power consumption [kW]
Minimum	58.62
Average	64.84
Maximum	73.45

Source: Authors.

Table 4 represents the compilation of parameterized results for the energy consumption of both chambers summed including diferente analysis at the same time. Results are described for minimum, average and maximum energy consumption. The average energy consumption is approximately 65 kW.

The cooling process regime which led to the minimum power consumption was obtained with RPF insulation for its better thermal and mechanical properties as indicated in Oliveira (2021). A 0.15m insulation thickness and the lowest entrance temperature of 5°C and 2.5°C for apples and fresh pork, respectively, were considered.

This regime represents an energy saving of about 20.19% (14.83kW) for the evaporator unit when compared to the maximum regime, using EPS insulation with higher thermal conductivity coefficient, 0.05m thickness, and entrance temperature of 15°C and 7.5°C, for apples and fresh pork, respectively.

The parametric study showed the importance of finding the optimal parameters for the cooling chamber operation since costs and environmental damages can be minimized.

4. Conclusion

A computer program is presented to calculate the thermal load for the design of cooling chambers intended for food storage. The model was validated for a specific case where thermodynamic properties of the products and psychrometric data from Belém city were known. The computer program aimed to perform a parametric study of the conduction and product thermal load as a function of the insulation thickness and the entrance temperature of the product.

An overall thermal load analysis showed that the minimum operation regime of the cooling chamber is about 20.19% lower compared to the maximum regime providing reduced costs and keeping product quality.

The study presents the criteria for energy reduction of the evaporator unit when choosing the type and thickness of insulation and maintenance of entrance temperature of precooling products.

It was verified that increasing the thermal insulation thickness and lowering the entrance temperature of the products to be stored contributes to reducing the required thermal load of the cooling chamber.

It can be highlighted the importance of a thermodynamic and heat transfer analysis to evaluate the different operational regimes of a cooling chamber. Find the optimal parameter values that meet the project premises results in the efficient energy consumption of the whole refrigeration system.

To continue this research, it is recommended the energy assessment with different refrigerant fluids for the same design assumptions; the implementation of economic sensitivity assessment to the developed computational code; the comparison of the results with an absorption refrigeration system and; the development of the exergoeconomic assessment of the proposed unit.

Nomenclature

A = Superficial area

Api = Floor area

Ce = Specific Heat of the product

Df = Doorway flow factor

Dt= Decimal portion of the time doorway is open

Dto= Occupation rate

E = Door protection system effectiveness

H = Latent heat of solidification

M = Mass of the product

K = Thermal conductivity

Np = Number of occupants

Q = Sensible and latent heat load for the prescribed flux

Qc = Conduction heat transfer rate

Qeq = Heat dissipated rate by the occupant

Qi = Heat illumination load

Qif = Outdoor air heat infiltration load

Qo = Occupation heat load

Qp = Sensible heat transfer

Qph = Latent heat transfer

Te = Outside temperature

Ti = Inside temperature

Tr = Cooling time

U = Overall heat transfer coefficient

Wi = Illumination rate

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