RIGA TECHNICAL UNIVERSITY

Dzintars JAUNZEMS

STUDY ON THE USE OF SOLAR THERMAL ENERGY FOR COOLING OF BUILDINGS

Dissertation Summary

Riga 2011

RIGA TECHNICAL UNIVERSITY
Faculty of Power and Electrical Engineering
Institute of Energy Systems and Environment

Dzintars JAUNZEMS
Environmental Engineering Doctoral Program

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Riga 2011

UDK 697.1(043)
Ja 938 s

Jaunzems D. Study on the use of solar thermal energy for cooling of buildings. Dissertation summary.-R.: RTU, 2011.-32 pages.

Published in accordance with the resolution of Riga Technical University, Institute of Energy Systems and Environment Protocol No 10/09-05-2011, May 9, 2011.

ISBN 978-9934-10-178-6

DISSERTATION
NOMINATED FOR THE SCIENTIFIC DEGREE OF DOCTOR OF ENGINEERING SCIENCES AT RIGA TECHNICAL UNIVERSITY

This study will be publicly defended on 9th of September, 2011 at 14:00 in the 21st auditorium of the Faculty of Power and Electrical Engineering, Kronvalda Boulevard 1, Riga.

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STATEMENT

I confirm that I have personally developed this dissertation which I have submitted for consideration at Riga Technical University for attaining the degree of doctor of engineering sciences. This study has not been submitted to any other university for attaining a scientific degree.

Dzintars Jaunzems…………………………….(Signature)

Date: ………………………

This dissertation is written in Latvian and contains an introduction, five chapters, conclusions, bibliography, two appendixes, 21 tables and 67 figures. The total volume comprises 150 pages. The bibliography contains 97 references.

This work has been supported by the European Social Fund within the project "Support for the implementation of doctoral studies at Riga Technical University".

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Background, current situation and relevance of the work

Europe 2020 is the EU's growth ambitious strategy for the coming decade. Each Member State has national targets to reach in the climate and energy sector. This calls for in-depth research and analysis addressing energy and environment sectors.

Energy consumption of the building sector accounts for nearly half of the total Latvian energy end-use consumption. Therefore, energy efficiency actions and integration of renewable energy sources in this sector are urgently needed.

Energy use for air conditioning of buildings is constantly increasing, even in northern countries like Latvia. Reduction of primary energy consumption for cooling should be based both on the energy efficiency measures and then on using renewable energy sources. However, comprehensive study for selecting energy efficiency improvement measures to minimise cooling load and use of renewable energy sources to cover building cooling load are missing in Latvia.

Solar cooling systems are an attractive technology to cover cooling loads. However, in Latvia these systems are not known and generally not considered feasible. The operation of solar cooling system under Latvian climatic conditions has not been sufficiently assessed and evaluated in depth.

The accurate determination of building cooling load is an important factor for selecting the most suitable type and capacity of solar cooling system. First of all it is essential to evaluate and model the fluctuations of cooling load in building, which include non-stationary heat exchange processes; then to select a proper solar cooling system, which is technically and economically feasible with a minimal impact on the environment.

Aim and objectives of the work

The aim of this thesis has been the development of a method for: (I) the determination of time-varying cooling load in buildings and (II) the sizing of solar cooling system and the evaluation of system performance to cover building cooling load under Latvian climate conditions.

The following tasks have been set in order to achieve the defined aim:

1. Development and validation of a building dynamic model for accurate determination of cooling load. The model is named “CooL”.
2. Analysis of the impact of energy efficiency measures on the cooling load. This analysis has been verified on a real case study with the aim to minimise building cooling load and cooling load duration curve.
3. Experimental analysis on solar collectors installed with reflectors with aim to increase performance and energy output in Latvian climate conditions.
4. Parameter identification of solar cooling system to cover building cooling load and development of a simulation model for a solar cooling system under Latvian climate conditions in the transient system simulation tool TRNSYS.

5. Analysis of the energy performance and assessment of economic and environmental impact of the simulated solar cooling system under Latvian climate and boundaries conditions.

Methodology of the research

The research methodology is based on system dynamic simulation and experimental analysis.

For the determination of building cooling load and its fluctuation the author has developed a calculation model named "CooL". With this model the analysis of the impact of energy efficiency measures on the cooling load was carried out.

For covering cooling load with solar energy driven system, an experimental analysis on vacuum tube solar collectors installed with reflectors was conducted. Statistical time-series processing techniques were used for processing experimental data.

Then, solar thermal energy driven absorption cooling unit was simulated in TRNSYS, which is a flexible software environment used to simulate the behavior of transient systems, for parameter identification to cover building cooling load.

The environmental and economic aspects were evaluated based on the simulation results for Latvian climate and boundary conditions.

Scientific significance

The main scientific significance of this thesis is the comprehensive study on use of solar thermal energy in cooling of buildings for Latvian climate and boundary conditions. It includes development of a calculation model, analysis of energy efficiency measures on cooling load and simulation of solar cooling system. Based on these analyses, environmental impact and economic aspects are evaluated.

Practical significance

This work has a high practical significance. There is a broad target audience for the developed work, while the application of the work depends on the objectives of the user.

The study can be used by:

- State institutions: The Ministry of Environmental Protection and Regional Development and The Ministry of Economics – the results from this thesis are useful for the development of action plans and design of support schemes addressing energy efficiency and renewable energy.
- The commercial sector: consultant, design companies, investors and private persons:
    - to plan energy efficiency measures and determine the influence of these measures on of cooling loads.

- to size and select solar cooling system and to evaluate the implementation and maintenance of such a system, including technical barriers and environmental and economic analysis.

Approbation

The results of the thesis have been reported and discussed in:

1. The 51st International RTU Scientific Conference with the paper “Small Scale Solar Cooling Unit in Climate Conditions of Latvia: Environmental and Economical Aspects” in Riga, Latvia, 12-13 October, 2010.
2. The 50th International RTU Scientific Conference with the paper “Influence of Thermo-dynamic Properties and Thermal Inertia of the Building Envelope on Building Cooling Load” in Riga, Latvia, 14-16 October, 2009.
3. The 3rd International Conference “Solar Air-Conditioning” with the paper “Applications of Solar Cooling Technologies in Buildings in Latvian (North-eastern Europe) Climate Conditions” in Palermo, Italy, 30 September – 2 October, 2009.
4. The International Scientific Conference “CISBAT 2009 Renewables in Changing Climate – From Nano to Urban Scale” with the paper “Integration of Renewables to Cover Cooling Load of Building. Feasibility and Application” in Lausanne, Switzerland, 2-3 September, 2009.
5. The Regional Conference “Environment and Energy in Vidzeme region” with the paper “Estimate of renewable energy resources use in Latvia up to 2020” in Valmiera, Latvia, 15th of May, 2009.
6. The 49th International RTU Scientific Conference with the paper “Development and Verification of Method for Building Cooling Load Calculation for Latvian Climate Conditions” in Riga, Latvia, 11-13 October, 2008.
7. The 11th International Conference “Solar Energy at High Latitudes” with the paper ”Trigeneration Heat, Power and Cooling” in Riga, Latvia, 30 May – 1 June, 2007.
8. The 48th International RTU Scientific Conference with the paper “Analysis of Trigeneration Heat, Power and Cooling Loads” in Riga, Latvia, 11-13 October, 2007.
9. International Scientific Conference “Pulp and Paper Industry Of Russia – Future View” with the paper “Simulation Model and Control Algorithm of Solar Combisystem”, in St. Petersburg, Russia, 26 October, 2006.
10. The 47th International RTU Scientific Conference with the paper “Development of Solar Combisystem Control Algorithm and Simulation Model” in Riga, Latvia, 12-14 October, 2006.

Publications

1. Jaunzems D., Veidenbergs I., Žandeckis A., Rochas C. The use of reflectors for increasing the energy performance of solar thermal collector in Latvian climate

conditions// Latvian Journal of Physics and Technical Sciences. – Riga: 2011. Vol. 5. – 7 p.

2. Jaunzems D., Veidenbergs I. Small Scale Solar Cooling Unit in Climate Conditions of Latvia: Environmental and Economical Aspects// 51th International Scientific Conference on Environmental and Climate Technologies. – Riga: RTU, 2010. – pp. 47–53.
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11. Jaunzems D., Rochas C. Simulation Model and Control Algorithm of Solar Combisystem// International Scientific Conference “Pulp and Paper Industry Of Russia – Future View” – St. Petersburg: St. Petersburg State Technical University VPO RP, 2006. – p. 128–132.
12. Jaunzems D., Rochas C. Development of Solar Combisystem Control Algorithm and Simulation Model// 47th International Scientific Conference Power and Electrical Engineering. – Riga: RTU, 2006. – pp. 133–144.

Thesis outline

The doctoral thesis is written in the Latvian language and consists of an introduction, five chapters, conclusions, two annexes and a bibliography. It contains 149 pages, 67 figures, 21 tables and a bibliography containing 97 literature sources. The summary does not include literature review.

1. Building dynamic cooling load calculation model

An accurate building cooling load and cooling energy consumption forecast is essential for choosing a building cooling system and optimal operation parameters. It is necessary to apply a dynamic calculation model to simulate building cooling load which takes into account all non-stationary heat exchange processes that occur simultaneously.

A calculation model "CooL" has been developed in this chapter. The model is largely based on the Standard ISO EN 15255:2007 "Thermal performance of buildings - Sensible room cooling load calculation - General criteria and validation procedures" and the methodology for building cooling load calculation described in the Standard. The methodology allows determination of:

1) Building hourly cooling load;
2) Building indoor temperature fluctuation profile.

The dynamic cooling load calculation model is supplemented by author with various options for processing and analysing the results and allows for the simulation of:

a) The geometrical, optical, stationary, and dynamic parameters of the building envelope and the influence of various energy efficiency measures on the building cooling load;
b) The influence of the building's indoor microclimate fluctuations on the building cooling load;
c) The influence of changes in tenants' behaviour and habits on the building cooling load.

Developed calculation model network is based on resistance and capacitance pattern. The network nodes of the building's dynamic calculation model "CooL" and developed networks are shown in the figure 1.1.

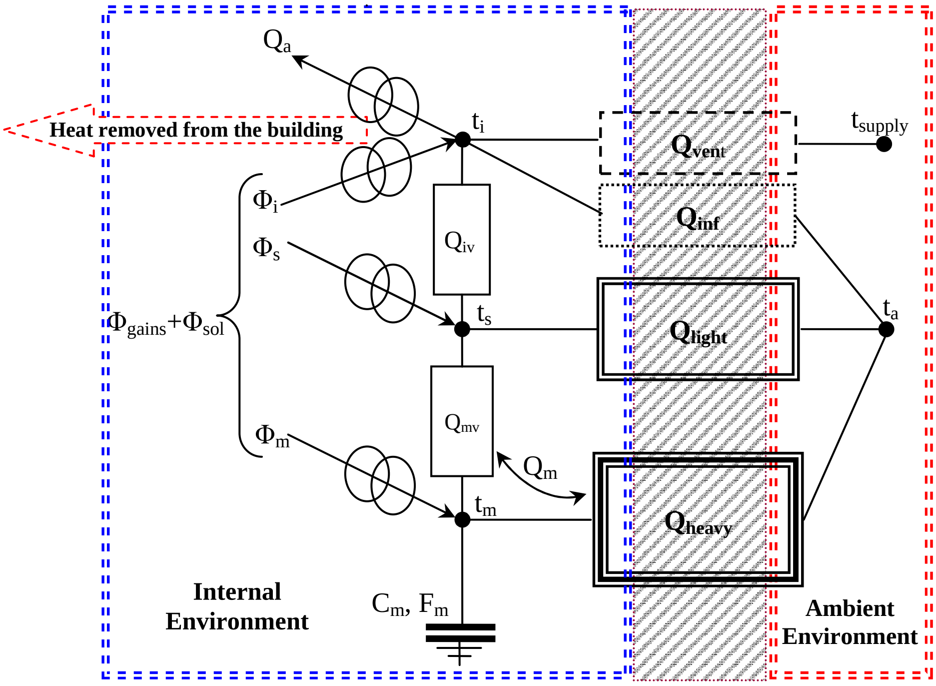


Fig. 1.1. Network nodes of the building dynamic cooling load calculation model "CooL"

The symbols shown in figure 1.1.:

a) t_{supply} – temperature of the air supplied to the ventilation system, °C;
b) t_{amb} – ambient air temperature, °C;
c) t_i – building indoor temperature, °C;
d) t_m – temperature of the building envelope thermal mass, °C;
e) t_s – building envelope surface temperature, °C;
f) Q_{vent} – ventilation produced heat loss factor, W/K;
g) Q_{light} – lightweight transparent and non-transparent building construction heat loss factor, W/K;
h) Q_{heavy} – heat loss factor between ambient air and heavyweight building envelope, W/K;
i) Q_{mv} – heat loss factor between heavyweight building envelope and inner surface of the building envelope, W/K;
j) Q_m – heavyweight building envelope heat loss factor, W/K;
k) Q_{iv} – heat loss factor between inner surface of the building envelope and indoor air, W/K;
l) C_m – thermal mass factor of the building envelope, J/K;
m) F_m – building mass area equivalent, m^2;
n) Φ_{gains} – total heat flow from inner heat sources of the building, W;
o) Φ_{sol} – total heat flow in the building from solar radiance, W;
p) Φ_i – heat flow in interior temperature network node t_i, W;
q) Φ_s – heat flow in surface temperature network node t_s , W;
r) Φ_m – heat flow in building envelope thermal mass temperature network node t_m, W;
s) Q_a – building cooling load, kW.

1.1. Validation procedure

Validation procedures were based on the Standard ISO EN 15255:2007 "Thermal performance of buildings - Sensible room cooling load calculation - General criteria and validation procedures".

Results of validation shows that the deviation of the result from building cooling load calculation model „CooL" varies ±5% and precision complies with A-level since average relative building cooling load $rQ_a = 0{,}042$. This means that the developed calculation model can be practically applied. The results of the validation are summarized in table 1.1

Table 1.1.

The results of the building dynamic calculation model validation

Test nr.	Reference building cooling load $Q_{a,ref}$, W	Modelled building cooling load Q_a, W	Relative building cooling load rQ_a
1.	1683	1755	0,041
2.	1431	1435	0,003
…	…	…	…
15.	1967	2005	0,019
16.	2218	2270	0,023
Average relative building cooling load rQ_a			0,042

2. Research on building cooling load fluctuations

Developed calculation model "CooL" has been approbated on the research target building in this chapter. It includes an analysis of the influence of energy efficiency measures on the building cooling load and cooling load duration.

2.1. Research target building

The research target building is a typical three-storey building in Latvia with a relatively small proportion of transparent building envelope (~11%) and simple architecture. It is an office building with a ceiling height of 3 meters. The total usable floor area is ~ 772 m^2, where the cooling load is required only for 524 m^2. The amount of air in the building is equal to 1262 m^3/h, and the air exchange rate is 0.545 h^{-1}.

The walls are made of silicate and clay bricks and mortar, cement and lime plastering. The floor and cellar ceiling are made of concrete panels and a sand and slag mixture. The building has not been insulated.

Average building heat gain is 6 W/m^2. The building's internal heat gains consist of:

a) Heat gained from lighting: 720 W;
b) Heat gained from electronics and electrical appliances: 1532 W;
c) Heat gained from humans (metabolism): 900 W;
d) Heat gained from hot water circuit: 10 W.

Figure 2.1 shows simulated cooling loads and ambient air fluctuations for the research target building throughout the year considering that the set indoor temperature of the building in summer is less or equal 24 °C and heat gain is equal to 6 W/m^2.

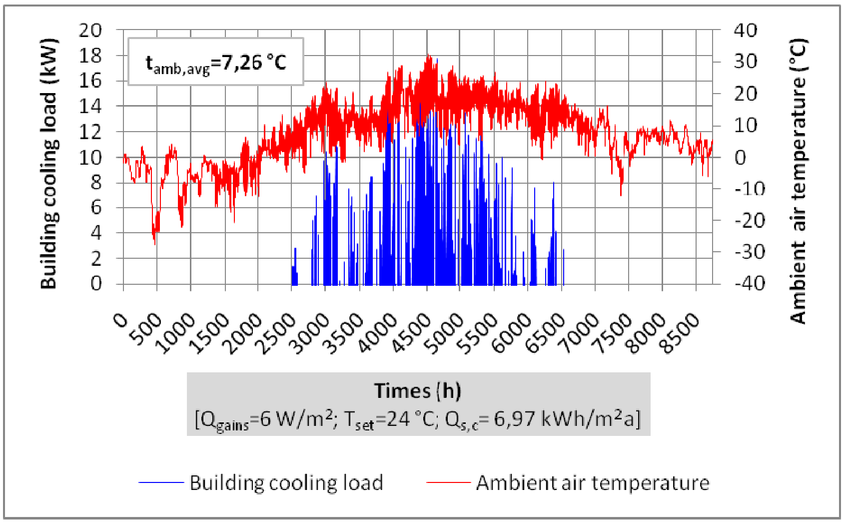


Fig. 2.1. The research target building's simulated cooling load and ambient air temperature fluctuations throughout the year

The cooling season for the research target building runs from the end of March to the beginning of October. The maximum cooling load of the research target building $Q_{c,max}$ is 17.8 kW$_c$, its specific cooling consumption $Q_{s,c}$ is 6.97 kWh/m^2 per year, and building cooling load duration t_c is 676 h/per year. The duration of the building cooling load t_c allows evaluation of the operation time for the cooling unit.

The research target building is classified as a lightweight construction according to the thermal mass classification. This means that the construction has a low thermal inertia and heat transfer between the interior spaces of the building and ambient environment is reasonably fast and no significant time offset between ambient air and inside temperature maximums and minimums is observed.

2.2. Influence of internal heat gains on the building cooling load

Practical experience and data obtained during energy audits indicates that the total average values of the building's internal heat gains vary from 2 to 50 W/m^2. These values depend on the type of the building, application and load modes. While heat gains in private houses normally do not exceed 10 W/m^2, in office building internal heat gains can reach 20–30 W/m^2.

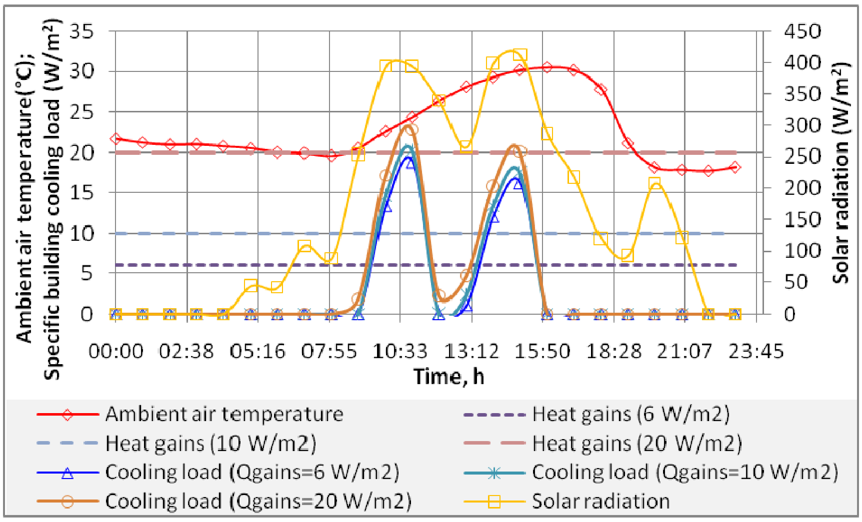


Fig. 2.2. Daily fluctuations of the research target building's simulated cooling load, ambient air temperature and solar radiation in July

Figure 2.2 shows that if a constant temperature is secured in the research target building, the building cooling load is constantly influenced by internal heat gains and only periodically by solar radiation intensity and ambient temperature. Moreover, solar radiation intensity only significantly influences the cooling load of a building if heat gains are considerably low (up to 10 W/m^2). If heat gain increases, the influence of solar radiation intensity and ambient temperature on the building cooling load decreases and the building's internal heat gains become dominant.

2.3. Influence of thermophysical and optical parameters of the building envelope

2.3.1. Influence of the building envelope heat transfer ratio

The building's specific cooling load and cooling load duration fluctuations depending on the building envelope heat transfer values have modelled. The quantitative experiment has been carried out for sixteen regimes. Results of the quantitative experiment (see Figure 2.3.) has showed that there is no correlation between the building's specific cooling energy consumption and the building's cooling load duration considering different building envelope heat transfer values. It can be explained by non-stationary heat exchange processes in the building and building envelope.

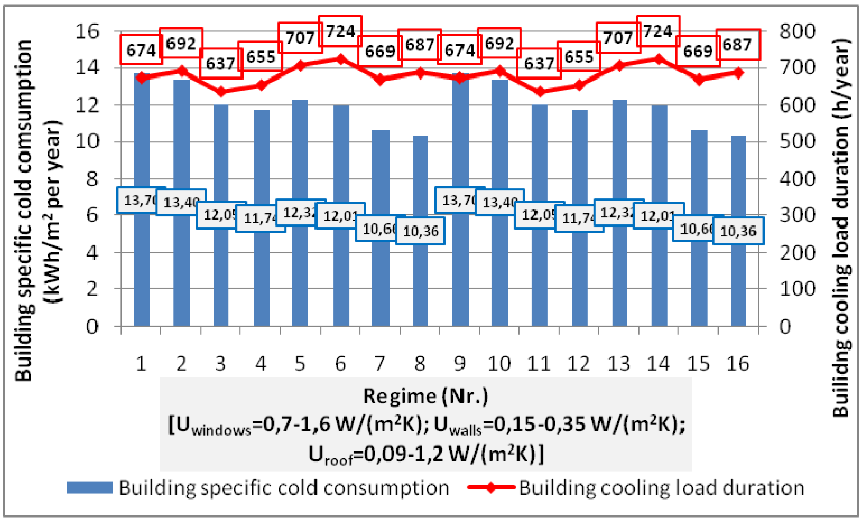


Fig. 2.3. The building's specific cooling consumption and building cooling load duration depending on the mode of the quantitative experiment

Figure 2.3 shows the building's specific cooling energy consumption and cooling load duration fluctuations depending on the wall heat transfer ratio.

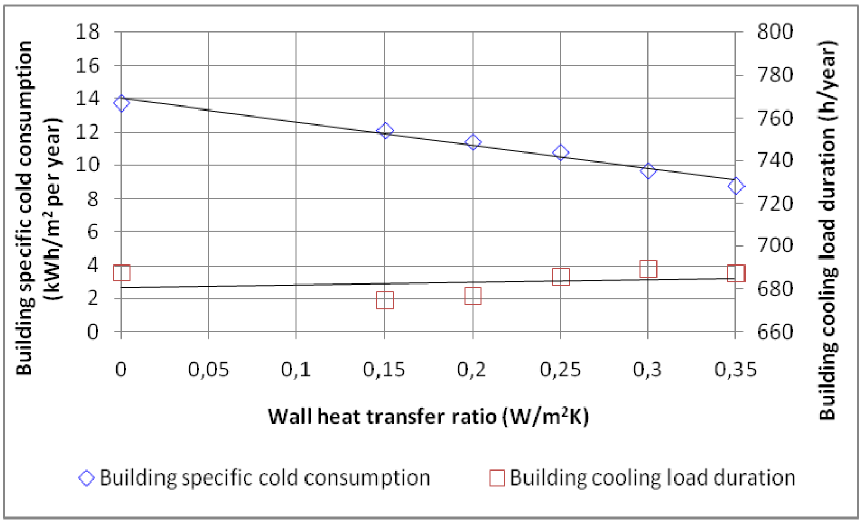


Fig.2.3. Changes of building specific cooling consumption and building cooling load duration depending on building envelope heat transfer ratio

When the wall heat transfer ratio increases, the building's specific cooling energy consumption decreases while cooling load duration increases. This is explained by heat flow increase between the interior and ambient environment, which facilitates natural cooling of the building if the ambient temperature is lower than the actual temperature inside the building.

In cases where building heat gains are larger than 10 W/m^2, in summer low building envelope heat transfer ratio values can significantly influence the building's cooling energy consumption and load duration. Since natural heat exchange processes and heat flows between the building's interior and environment are restricted, the building is not naturally cooling, for example, in nights.

2.3.2. Influence of the specific surface area of the building's transparent envelope

The glazed surface area of the building envelope is an important parameter for building description. The influence of this factor is significant because of the increasing influence of solar radiation heat flow on building heat gain.

Figure 2.4 shows that increase of transparent surface area leads to an increase in the building cooling load and a decrease in the thermal mass ratio. This means that the fluctuations in the building's interior temperature are influenced more by the solar radiation and ambient air temperature. It can be expected that increased inner temperature fluctuation range will negative effect the interior microclimate and comfort level in the building. Moreover, it will be more complicated to provide necessary temperature level inside the building. Therefore, the cooling load peak will increase over the 24 hour period.

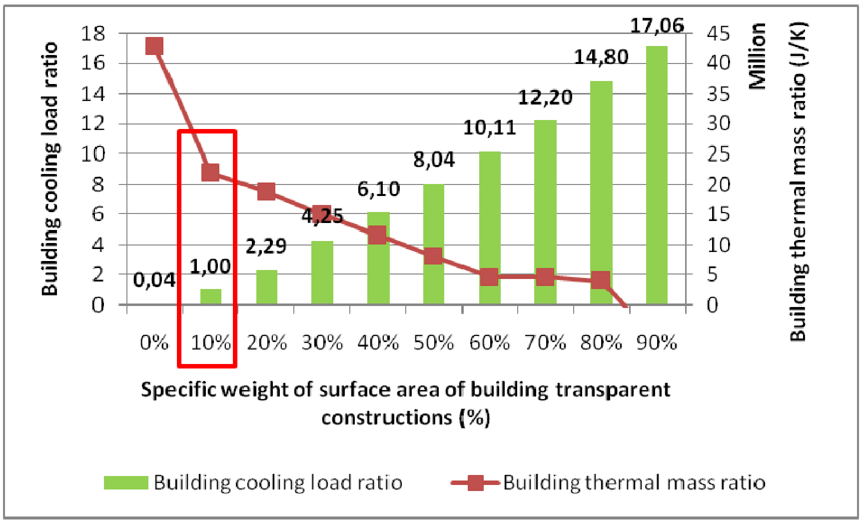


Fig.2.4. Changes of building cooling load ratio and building thermal mass ratio depending on the specific weight of the surface area of the building's transparent constructions

By increasing the building envelope transparent surface area, the proportion of natural illumination is increased. However, the influence of the transparent constructions and heat resistance during winter must also be considered.

2.3.3. Influence of building insulation

The aim of building insulation is to improve heat retention, which is especially important in the winter season when ambient temperatures are low. Insulation allows a reduction in the building's heat losses without significant changes in the building's thermal mass. At the same time, the influence of building insulation on the building's cooling load is not evaluated in Latvia.

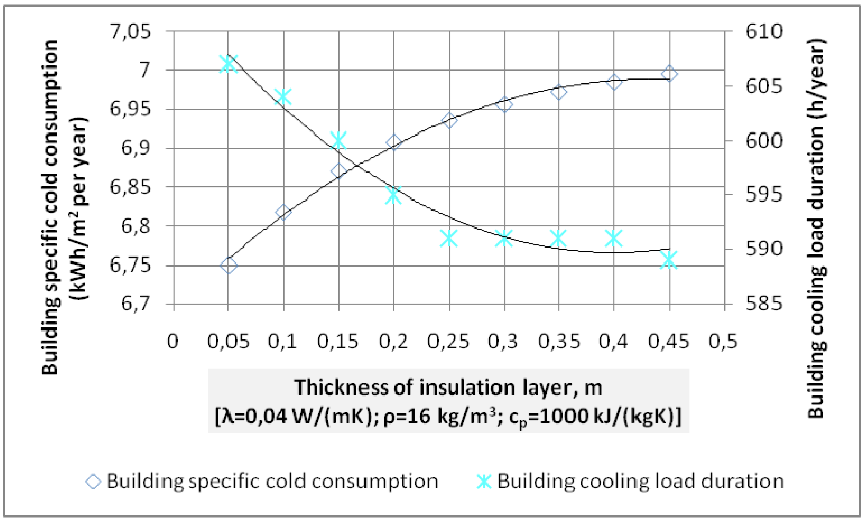


Fig. 2.5. Changes of building specific cooling consumption and building cooling load duration depending on thickness of heating insulation layer

The research target building is insulated with 5 cm step, widely available heat insulation material with heat conduction ratio λ=0,4 W/(mK), density of ρ=16 kg/m^3 and specific thermal capacity of c_p=1000 kJ/(kgK).

Figure 2.5 shows that if heat insulation thickness is increased, the building's specific cooling load increases while building cooling load duration is reduced. This can be explained by a reduction in the influence of solar radiation and ambient air temperature.

The building cooling load increase is related to changes in the heat flow from the building's interior to the environment. The peak building cooling load increases while the building cooling load duration decreases. This means that in order to provide the necessary temperature level in the building, it is necessary to use cooling equipment with a higher capacity for a shorter period of time.

2.3.4. Dynamic parameters of the building

The building's thermal inertia factors show the influence of the building's thermal mass fluctuations considering the dynamic nature of the building's interior temperature fluctuations. The general building thermal inertia factor fluctuations related to the wall insulation works are shown in the figure below.

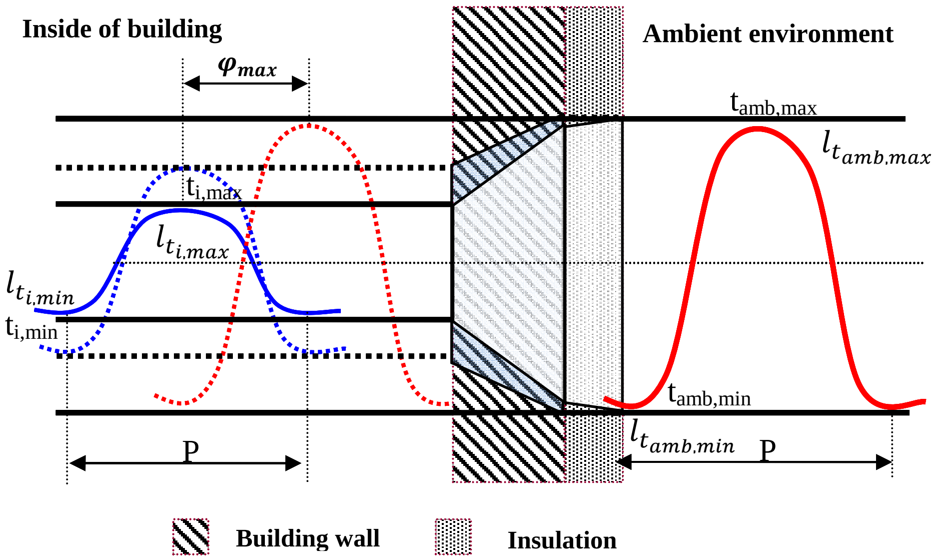


Fig. 2.6. Schematic graph of decrement factor *f* and time lag *φ* of maximum and minimum external air and internal temperature for building envelope with and without heating insulation layer applied

The building's interior temperature fluctuation range as well as offset of maximums and minimums depends on the ambient air temperature and thermophysical and geometrical characteristics of the building. Building insulation can help to reduce the building's interior temperature fluctuation range and reduce the influence of the ambient air temperature on the changes in the building's microclimate.

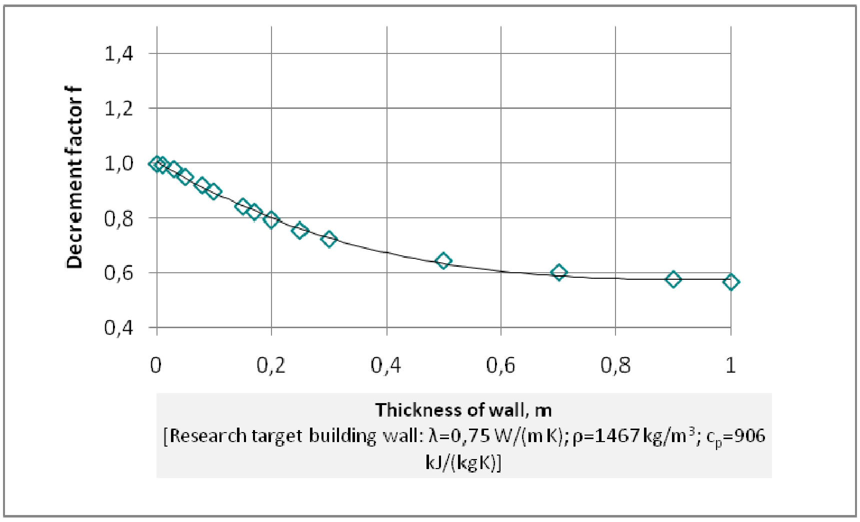


Fig. 2.7. Changes of temperature fluctuation amplitude decrement factor *f* depending on thickness of research target building wall

Figure 2.7. shows changes in the temperature fluctuation range decrement factor *f* depending on the wall thickness of the research target building. These changes are not linear, demonstrating that as the building thermal mass increases, the building thermal inertia also increases. Therefore, a reduction in the fluctuation range of the building's interior temperature can be observed, meaning that the 24-hour indoor temperature in the building begins to align.

3. Experimental study of the solar collector

An experimental study of the solar thermal system was performed from August 13th, 2010 to September 17th, 2010. The following parameters were measured and defined in the experiment:

1) Intensity of solar radiation S_{col}, W/m^2;
2) Ambient air temperature T_{amb}, °C;
3) Return temperature of the solar collector heat carrier $T_{col,in}$, °C;
4) Supply temperature of the solar collector heat carrier $T_{col,out}$, °C;
5) Heat capacity of the solar collector Q_{col}, kW;
6) Produced heat energy Q_{col}, kWh;
7) Heat medium flow v_{col}, m^3/h;
8) Volume of the heat carrier V_{col}, m^3;
9) Operational life of the solar collector t_{col}, h.

The experimental study of the solar collector was performed in two modes:

a) Without reflectors;
b) With reflectors.

The solar heat system operational parameters were defined for each of the modes, thus allowing a comparison of energy performance in both modes. The system for the vacuum tube collector experimental study is shown in figure 3.1.

Fig. 3.1. Experimental study system for vacuum tube solar collector

The solar thermal system consists of a vacuum tube solar collector, control unit, measurement devices, circulation pump, expansion vessel, circulation pump measurement device, pipe circuit, security, counter-pressure, flooding valve and dearerator.

The vacuum tube solar collector was oriented precisely to the South at an angle of 39° against horizontal. The solar collector system was installed in the village of Rāmuļi, Vaive Municipality, Cēsu Region, Latvia (GPS coordinates: 57.21155N, 25.414953E).

The vacuum tube solar collector energy efficiency parameters are shown in table 3.1.

Table 3.1.

Parameters of vacuum tube solar collector

Optical coefficient of performance of vacuum tube solar collector	η_0 = 0,717
Heat transfer coefficient	a_1 = 1,52 W/(m^{2}K)
Temperature-dependant heat transfer coefficient	a_2 = 0,0085 W/(m^{2}K^2)

A water and propylene glycol mixture in the ratio of 3 to 1 is used as a heat medium. The pump is used for circulating the heat medium liquid. The control unit is connected to the supply and ambient temperature sensors and regulates the operation of the circulation pump. A diagram of the vacuum tube solar collector experimental study prototype is shown in figure 3.2.

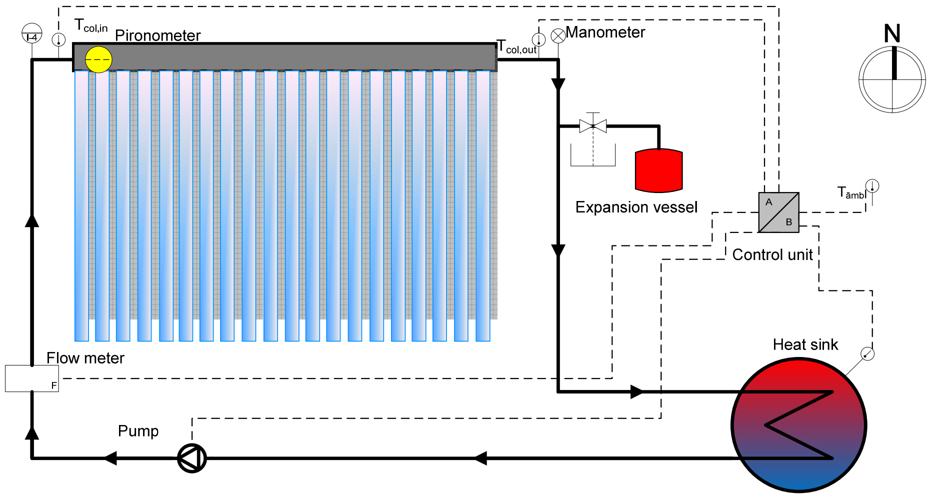


Fig. 3.2. Diagram of vacuum tube solar collector experimental study system

The following equipment and measurement tools were used to perform the experimental research:

1) Pyranometer;
2) Temperature sensors;
3) Heat meter with flow sensor and meter;
4) Circulation pump;
5) Expansion vessel;
6) Security valve;
7) Dearerator;
8) Flooding valve;
9) Solar collector circuit circulation pump control unit.

Uncertainty analysis of the solar collector capacity measurements showed that in order to reduce solar collector capacity measurement uncertainty, it is important to pay attention to the definition of solar radiation. As analysis of the uncertainty balance shows that solar radiation measurements contribute the largest input (75.5–99.96 %) to total uncertainty.

3.1. Analysis of the influence of reflectors on solar collector performance

Reflectors increase the intensity of solar radiation falling on the solar collector, thus improving the energy efficiency of the existing solar collector. Considering Latvian climatic conditions and operational aspects of the solar cooling system, optimal use of reflectors can improve the energy performance of the solar collector and improve economic performance.

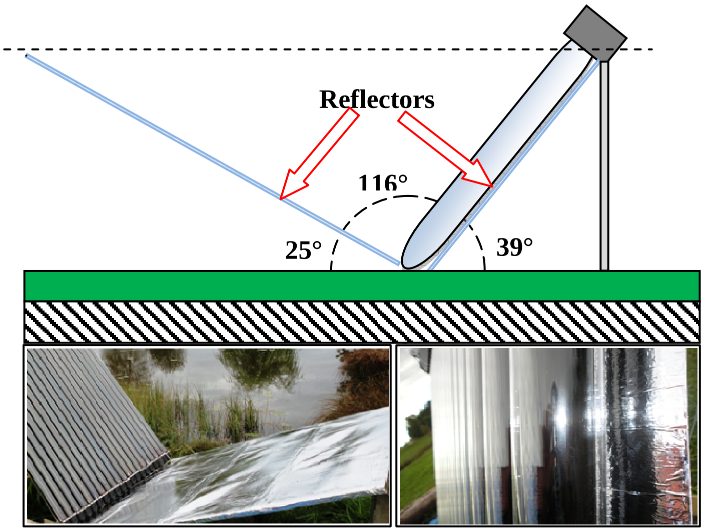


Fig. 3.3. Diagram of vacuum tube solar collector with reflectors and reflectors' location

Figure 3.3 shows a diagram of a vacuum tube solar collector with reflectors. The optimal reflector angle to the horizontal is assumed to be 25° according to literature data. Accordingly, the geometrical sizes of the reflectors were determined in accordance with the angles to the horizon of both reflectors and the collector and based on the geometrical parameters of the solar collector.

Based on an evaluation of the solar collector's actual performance ratio fluctuation (see fig. 3.4), it can be concluded that the solar collector coefficient of performance can be improved by using reflectors. A solar collector with reflectors can produce up to 7-10% more heat energy per received solar radiation energy unit than a solar collector without reflectors.

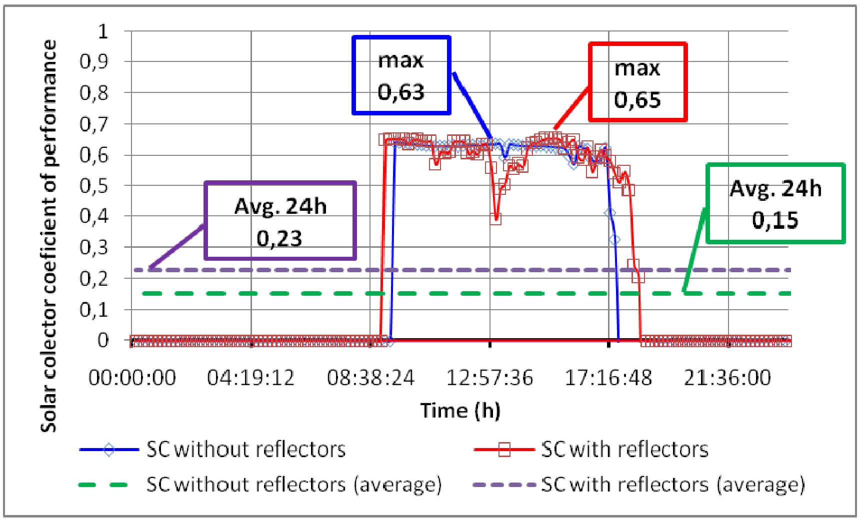


Fig. 3.4. Solar collector performance coefficient with and without reflectors

Although reflectors require additional investments and involve certain technical and aesthetic limitations, they can improve the performance and production indicators of solar collectors. Reflectors can also be considered as a technically and economically feasible solution for improving solar collector energy efficiency, especially for relatively large solar heat systems (F_{col} > 20 m^2).

3.2. Time series data processing

The obtained serial data and measurement results are based on the solar thermal system experimental study. The system was installed and operated from August 12th, 2010 till September 19th, 2010. Measurements were taken at ten minute intervals. The main measurement parameters were solar radiation intensity, heat medium input and output temperature from the solar collector and ambient air temperature.

The following two time periods were selected in accordance with the objectives of the experimental study and for more effective data processing:

1) 15th – 17th August, 2010 (solar thermal system installed without reflectors);
2) 12th – 14th September, 2010 (solar thermal system installed with reflectors).

Three time series statistical data processing methods were used:

1) Multiplicative and additive model of time series decomposition method;
2) Time series data moving average method with or without centring the moving average;
3) Single-stage and double-stage exponential smoothing method.

Time series data processing was performed with the widely-used statistical program MINITAB. Three precision parameters were used for all time series data methods:

1. Mean Absolute Percentage Error (MAPE);
2. Mean Absolute Deviation (MAD);
3. Mean Squared Deviation (MSD).

The three dynamic time series data processing method precision parameters are summarized in the table 3.2.

Table 3.2.

Accuracy measures of processing of dynamic time series data

Precision parameter	Time series decomposition method		Time series data moving average method		Exponential smoothing method	
	Multiplicative model	Additive model	With centring	Without centring	Single-stage	Double-stage
MAPE	226.57	204.46	318.25	210	177.33	185.01
MAN	47.0	34.07	34.3	23.73	18.94	20.48
MSD	7200.20	4027.04	5563.28	2894.45	3081.74	3407.26

The single-stage exponential smoothing method achieved the most precise parameter indicators. This means that this method most accurately describes solar collector heat capacity fluctuations. Analysis of real and obtained time series processing data is shown in figure 3.5.

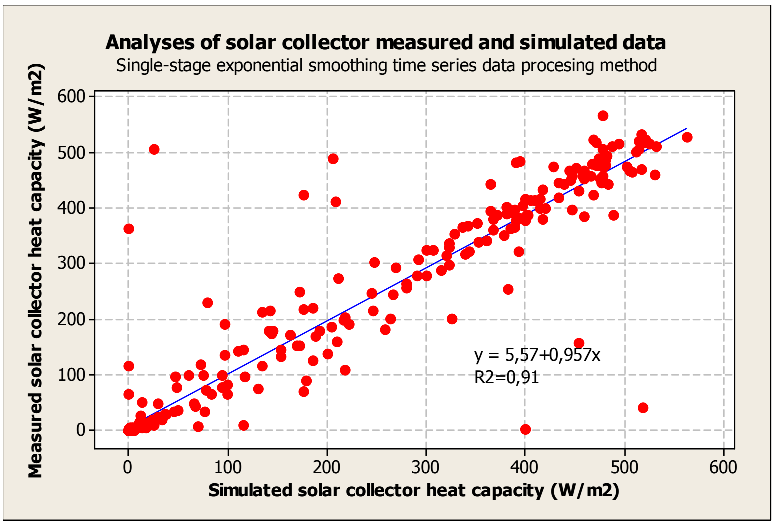


Fig. 3.5. Analyses of the measured and simulated data of solar collector heat capacity

Based on analysis of the three time series data processing methods that were performed, the single-stage exponential adjustment method and its relationships can be used for describing solar collector heat capacity in Latvian climatic conditions.

$$Q_{col,mod_{l_n}} = \alpha Q_{col_{l_n}} + (1+\alpha) Q_{col,mod_{l-1}} =$$
$$= \alpha\left(0{,}53 S_{l_n} + 2{,}11\left(T_{amb_n} - \frac{T_{col,in_n}}{2}\right) + 4{,}02\right) + (1+\alpha)\cdot$$
$$\cdot\left(F_{kol}\left[S_{l-1}\eta_o - a_1\left(T_{amb_{l-1}} - \frac{T_{col,out_{l-1}} + T_{col,in_{l-1}}}{2}\right) - a_2\left(T_{amb_{l-1}} - \frac{T_{col,out_{l-1}} + T_{col,in_{l-1}}}{2}\right)^2\right]\right), \quad (3.1.)$$

where $Q_{col_{l_n}}$ – solar collector heat capacity in point n of the time series, W;

α – smoothing constant;

S_{l_n} – solar radiation in point n of the time series, W/m^2;

T_{amb_n} – ambient air temperature in point n of the time series, °C;
T_{col,in_n} – solar collector inlet temperature in point n of the time series, °C;
$T_{col,out_{l-1}}$ – solar collector outlet temperature in point $l-1$ of the time series, °C.

Solar collector heat capacity fluctuations are dependent on ambient temperature, solar radiation intensity, solar collector optical and thermophysical parameters (see equation 3.1.).

Considering the fact that each subsequent simulated collector heating capacity value depends on the preceding one, general solar collector capacity fluctuations can be shown as following the single-stage exponential smoothing method:

$$Q_{kol,mod_{l_n}} = \alpha Q_{col_{l_n}} + (1+\alpha) Q_{col,mod_{l-n}}, \qquad (3.2.)$$

where n – point of the time series;
$Q_{col,mod_{l-n}}$ – simulated solar collector heat capacity in l-n point of the time series, W/m^2.

The obtained empirical relationships (3.1) and (3.2) can be used to define the solar collector's heating capacity and component parameters for Latvian climatic conditions depending on solar intensity, ambient temperature and the solar collector's optical and thermophysical parameters.

4. Simulation of a solar cooling system

Simulations of solar cooling system for research target building in Latvian climate conditions have done in this chapter.

Simulation of the solar cooling system is based on the selected research target building, where maximum cooling load $Q_{c,max}$ is 17.8 kW$_c$, cooling load duration t_c is 692 h/year and specific building cooling energy consumption $Q_{s,c}$ is 6.97 kWh$_c$/m^2 per year where the defined indoor temperature of the building t_{set} equals 24 °C. Figure 4.1 shows a diagram of the solar cooling system.

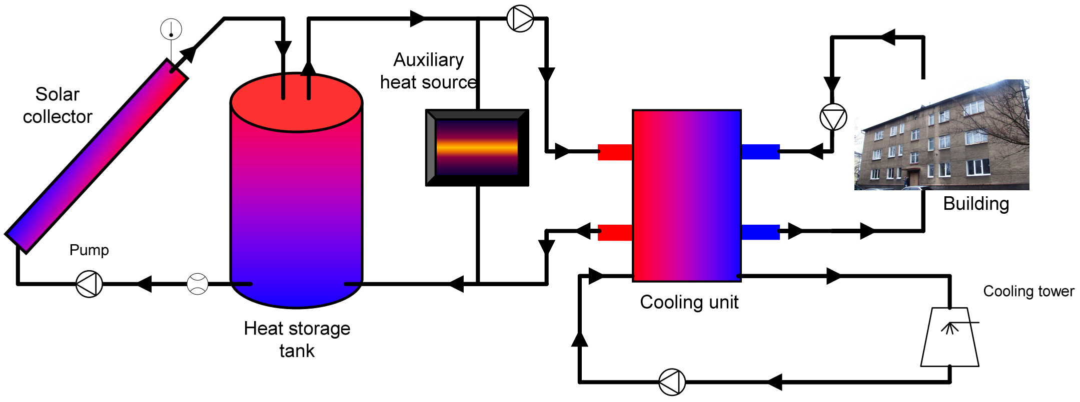


Fig. 4.1. Diagram of simulated solar cooling system

Based on the literature review, in order to cover the cooling load of the building an absorption type cooling system available in the market with nominal cooling load of 20 kW_c was selected. Solar collector array was planned to cover 80% of total heat consumption of heat driven absorption cooling unit.

4.1. Solar cooling system model in TRNSYS

The TRNSYS simulation program was used to simulate the solar cooling system and evaluate its operation. This simulation program has a modular structure which makes it possible to divide the existing system into mutually connected components (solar collector, cooling unit, etc.). Each component is simulated separately using mathematical relations available in the TRNSYS data base or which can be developed using different data processing programs or programming languages e.g. MS Excel, Matlab or C++.

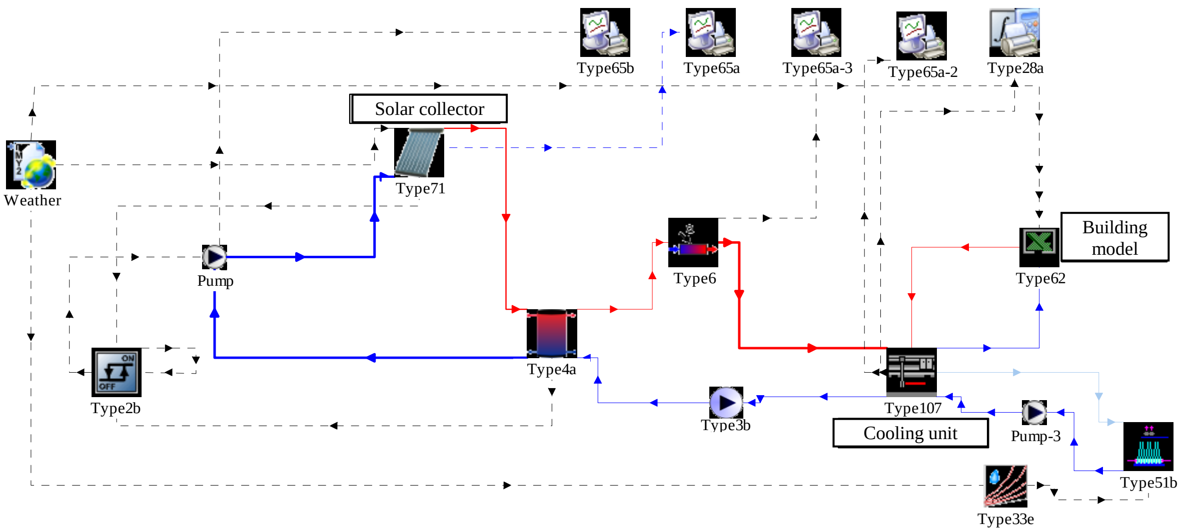


Fig. 4.2. Diagram of simulated solar cooling system in the environment of TRNSYS simulation program

Solar collector have simulated with component Type71. Heat driven absorption cooling unit have simulated with Type 107. Building model has been integrated as outsource component using component Type 62 from TRYNSYS data base. The calculation model "CooL" has used for input file for component Type 62. A diagram of the solar thermal system and the model in the TRNSYS environment are shown in figure 4.2.

4.2. Analysis of solar cooling system simulation results

The nominal heating capacity required for cooling equipment depends on the cooling load of the building, the nominal capacity of the respective cooling equipment and the nominal performance ratio of the cooling equipment. The parameters of the cooling equipment are provided in the technical specification or other supporting documents.

In order to provide the stated fraction of 80% of solar energy in Latvian climatic conditions, the specific area of the installed solar collector varies from 3 to 5 m^2/kW_{cold} depending on the type of the collector.

Thus the capacity of the solar accumulation tank depends on the solar thermal system and varies from 40 to 75 l/m^2. Heat medium flow is provided by a circulation pump (max flow is 200 kg/h).

The solar energy fraction describes how much of the heat with a definite temperature level required for the cooling equipment can be provided by the solar thermal system. The gap heat energy must be provided by an additional heat source. As demonstrated by the solar system simulation results show in figure 4.3, the solar energy fraction depends on the type and area of the solar collector installed.

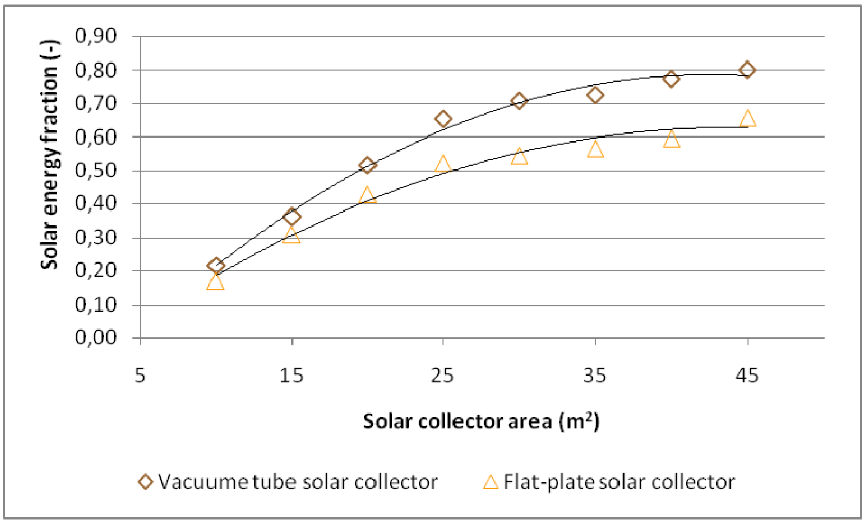


Fig. 4.3. Changes in solar energy supply depending on solar collector type and nominal area

In order to provide solar energy fraction of 80%, cooling equipment with 20 kW_c nominal capacity requires a 45 m^2 vacuum tube solar collector.

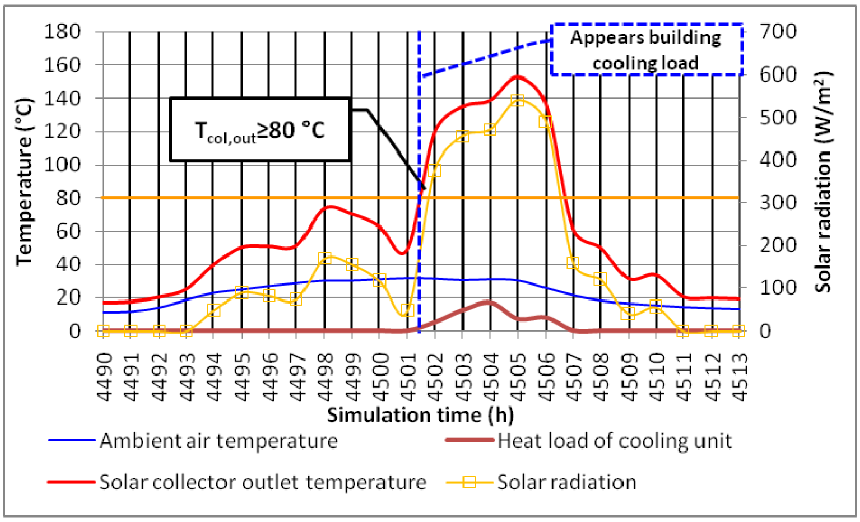


Fig. 4.4. Required changes in heating load of cooling device and supply temperature of solar collector (area 45 m^2)

Figure 4.4 shows the temperature and cooling equipment heat load fluctuations of a simulated solar collector with 45 m^2 area. If the solar thermal system had a smaller heat collector area or flat solar collectors were used, an additional heating source would have to be used to ensure the necessary temperature level for the cooling equipment.

The results of the experiment and the performed simulation (see fig. 4.3) prove that vacuum tube solar collectors are more efficient and suitable for operating in a higher heat medium temperature mode and are able to provide the required heat energy level with less installed area. Moreover, this type of collectors has a higher stagnation temperature level (>180-200 °C).

A solar thermal system with a 45 m^2 vacuum tube solar collector is able to provide the required temperature gradient for the cooling equipment and cover almost 4200 kWh i.e. 80% of all the heat energy required for the cooling equipment.

4.3. Analysis of solar cooling system environmental and economic parameters

4.3.1. Reduction of CO_2

One of the most commonly applied parameters for evaluating the environmental impact of a technology is CO_2 emission reduction, which describes the CO_2 reduction potential of the selected equipment considering the CO_2 factor of the reduced or substituted energy.

In light of the above mentioned facts, four feasible CO_2 reduction scenarios have been analysed:

1) Scenario A: CO_2 reduction applying thermal cooling equipment at an average traditional cooling equipment performance ratio η_{trad}=2.5;
2) Scenario B: CO_2 reduction applying thermal cooling equipment at maximum traditional cooling equipment performance ratio η_{trad}=4.5;

3) Scenario C: CO_2 reduction applying solar thermal system and thermal cooling equipment at an average traditional cooling equipment performance ratio η_{trad}=2.5;
4) Scenario D: CO_2 reduction applying solar thermal system and thermal cooling equipment at maximum traditional cooling equipment performance ratio η_{trad}=4.5.

The following CO_2 emission factor values were used in the analysis:

a) For solar energy: 0.264 kg_{CO_2}/kWh_{th};
b) For electricity: 0.397 kg_{CO_2}/kWh_{el}.

It was assumed in all of the scenarios that the solar energy part is 80% and the performance ratio of the thermal cooling equipment is η_c=0.6.

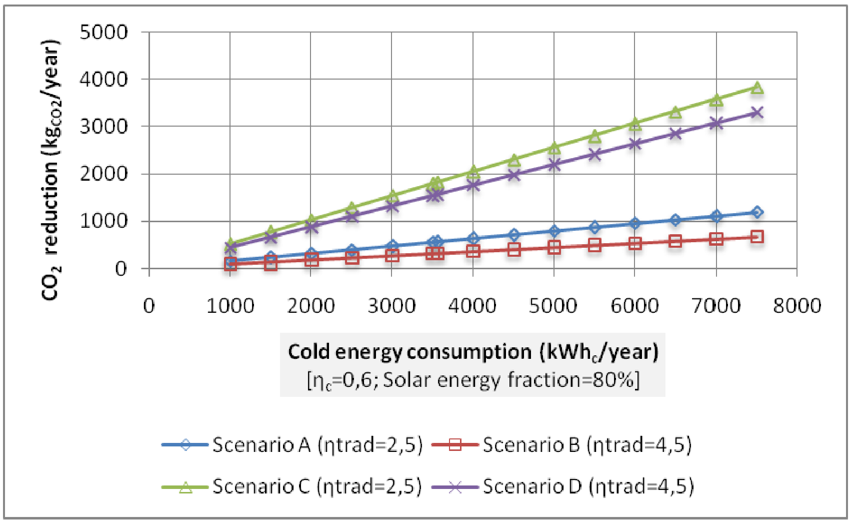
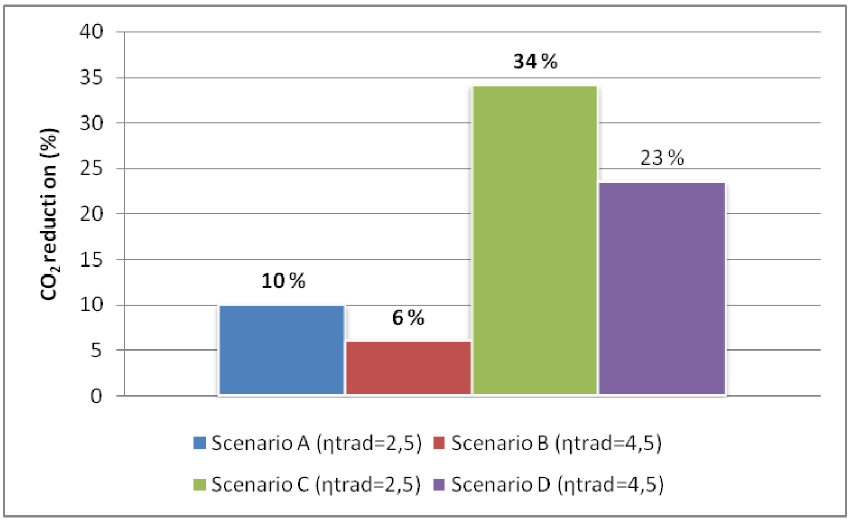


Fig. 4.5. CO_2 reduction depending on cooling energy consumption

Figure 4.5 shows that CO_2 reduction at the assumed performance ratio of the thermal cooling equipment η_c and fraction values for the solar energy depends on cooling energy consumption.

In a situation where the solar cooling system is operated with a higher load, the expected CO_2 reduction increases. The average CO_2 reduction when applying solar cooling system and considering calculation assumptions varies from 0.088 to 0.511 kg_{CO_2}/kWh_c.



4 Fig. 4.6. CO_2 emission reduction

Figure 4.6 shows that by using a solar cooling system instead of traditional cooling equipment, the CO_2 emission volume is reducedby 10-30%. Thus, it can be concluded that solar cooling systems have high CO_2 reduction potential and they can be used for CO_2 emission reduction and to achieve the set goals for the energy sector.

4.3.2. Annuity method

In accordance with the economic analysis which is based on the annuity method, all money flows related to installation of the solar cooling system are converted into equally divided yearly cost flow A, which is obtained by calculating current net payment value in different time periods and discounting all the payments to the beginning of the period ($t = 0$).

Prices of cooling equipment and solar thermal systems are based on the literature review and market analysis. The specific initial investments in the solar cooling system range from 1,700 to 3,500 LVL/kW$_c$. In comparison with the specific initial investments for traditional cooling equipment –which range from 45 to1000 LVL/kW$_{c,}$ these costs are high and are not attractive to potential users without financial support mechanisms or subsidies.

According to Bank of Latvia data, the average inflation rate in Latvia in 2010 was 3.7%. A discount rate of 4% was used. According to the producer's information, the operating life for absorption type cooling equipment is 25 years. The operating life N for all solar cooling systems is considered to be 20 years.

In order to define yearly costs A, the current net value is multiplied by the previous value recovery factor r_f, which is obtained from the discount rate d and system operating life N.

$$A = CNV \cdot r_f(N, d) = PNV \cdot \frac{d(1+d)^N}{(1+d)^N - 1}, \qquad (4.1.)$$

where CNV – current net value, LVL;

r_f – previous value recovery factor;

d – discount rate, %;
N – operating life, years.

In order to compare solar cooling systems with traditional cooling supply solutions, normalised cooling energy costs are applied. Normalised cooling energy costs are expressed as a relation of yearly costs A and cooling energy consumption Q_{cold}.

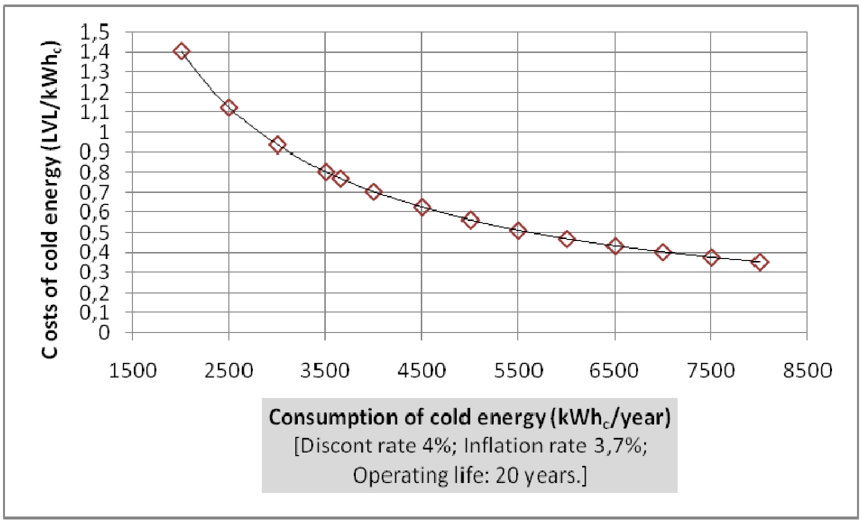


Fig. 4.7. Cooling energy costs depending on annual consumption of cooling energy

Figure 4.7 shows that the economic benefits of the analysed solar cooling system are influenced by yearly consumption of cooling energy. If the annual consumption of cooling energy increases, the costs per unit of produced cooling energy are reduced. However, due to sharp decreases in market prices for solar energy technologies, consistent growth in electricity tariffs, CO_2 trading prices, fluctuations in macroeconomic indicators and advances in scientific research in this field, it is expected that solar cooling systems will become economically feasible and will promote the use of renewable energy sources, thus helping to achieve the set objectives in the energy sector.

Conclusions

1. The methodology for selecting heat driven equipment for cooling has been developed and approbated on the research target building for securing indoor temperature in summer. The methodology based on:
    - modelling of geometrical, optical, stationary and dynamic parameters, as well as influence of energy efficiency measures on the building cooling load, duration of the building cooling load, and indoor temperature of the building;
    - evaluation of solar collector performance and heat production in Latvian climate conditions;
    - simulation of solar cooling system operation and analysis of environmental and economic aspects of its use.

2. The dynamic cooling load calculation model “CooL” has been developed and validated for Latvian climate conditions. The impact of various energy efficiency measures and parameter fluctuations on the building cooling load, building cooling load duration and indoor temperature have been simulated for the research target building for defined indoor temperature.
3. Analysis of the simulation results for the impact of building cooling load, building cooling load duration and indoor temperature fluctuations prove that:
    - Increases in indoor heat gain are not linear. If the heat gain value exceeds 10 W/m^2 under unchangeable building envelope parameters, a rapid building cooling load increase is observed, since heat gain becomes a dominant source of the building cooling load. At heat gain below 10 W/m^2 building cooling load is mainly influenced by the ambient temperature and solar radiation;
    - An increase of the building envelope heat transfer ratio at unchangeable heat gain leads to a non-linear reduction of the specific building cooling load consumption and insignificantly influences building cooling load duration, since a more intensive natural cooling of the building occurs; when thermal resistance of the building envelope decreases, heat exchange between the building’s indoor rooms and the ambient environment increases;
    - An increase in the proportion of the building envelope transparent area decreases the thermal mass of the building and results in an increase of the building cooling load. If the glazed surface area exceeds 60% of the total area, higher indoor temperature fluctuations occur since heat energy accumulation in the building envelope decreases;
    - If building insulation is installed, building cooling energy consumption increases non-linearly with constant heat gain. The increase depends on the thickness of the insulation layer. The building cooling load duration decreases. This happens because of reduced heat exchange between the building’s indoor premises and the ambient environment;
    - When the thickness of the building wall increases, the building’s thermal mass also increases while temperature fluctuations in the building indoor premises decrease under constant heat gain, all of which has a positive impact on the building’s microclimate. At the same time, significant thickness of the heat insulation (more than 0.1–0.15 m) under constant heat gain leads to increased indoor temperature fluctuations for the building since the heat gain created by heat flow from the building’s indoor premises to the environment is reduced.

4. An experimental study using a vacuum tube solar collector was performed in order to define its heating capacity depending on the ambient air, supply and return temperatures of the heat medium and solar radiation intensity. The experimental data is described by trends, repeating patterns, seasonality, and random components. For this reason the data was processed using time-series methods. The obtained empirical

relationship can be used to evaluate solar collector installed with reflectors operations in Latvian climatic conditions.

5. A study was conducted on building cooling load coverage with solar thermal energy driven absorption-type cooling equipment. A solar cooling system study using a simulation program TRNSYS integrating the calculation model "CooL" as an external data source was conducted. The results of the simulation analysis showed that solar heat energy can cover a significant part of the heat energy needed for the cooling equipment from the technical and energy aspects. A solar cooling system for the target building with a total collector area of 45 m^2 and installed cooling equipment capacity of 20 kW_c can cover up to 80% of the total heat energy requirements for the cooling equipment.
6. Simulation of the flat solar collector and vacuum tube solar collector was performed TRNSYS program in order to provide the heat energy temperature level required for the cooling equipment in Latvian climatic conditions. Vacuum tube solar collectors can be used for the high temperature mode of the heat carrier (>70 °C), since lower heat losses are possible from the solar collector into the ambient environment and its stagnation temperature limit is higher (190–260 °C). Moreover, a smaller vacuum solar collector area is needed than with flat solar collectors.
7. Analysis of solar cooling system environmental aspects shows that in comparison with electrical energy operated compression-type cooling equipment, 10 to 35% of annual CO_2 emission output can be reduced depending on the cooling energy consumption of the respective building.
8. Analysis of solar cooling system economic aspects shows that under existing market prices for solar collectors and thermally operated cooling equipment, electricity tariffs and CO_2 trading prices, initial investments and operating costs are now lower than for traditional, compression-type cooling equipment used for building cooling supply systems. Moreover, rapid reductions in prices for solar energy technologies, increasing electricity tariffs and increases in CO_2 trading prices must also be taken into consideration.
9. Due to sharp decrease in market prices for solar energy technologies, constant increases in electricity tariffs and CO_2 trading prices, fluctuations in macroeconomic indicators and progress in scientific research in this field, it is expected that solar cooling systems will become economically feasible and will promote use of renewable energy sources, thus helping to achieve the set objectives in the energy sector.