Survey of the Climatic Behavior of Motor Homes
- An assessment of the hygrothermal performance of recreational vehicles

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ABSTRACT: In an increasingly mobile world, traveling with a motor home is becoming ever more popular.. People visit very different regions in every season. Maintaining a comfortable climate inside the vehicle is a basic requirement. In the context of a research program of the BBS INSTITUTE, University of Applied Sciences and Arts, HAWK Hildesheim, Germany, the thermal and energetic behavior of motor homes and the hygrothermal behavior of the exterior building elements were investigated depending on the surrounding climate, the user's behavior and the building elements. The results of this investigation indicate new possibilities for an overall assessment of motor homes and their construction. We developed basic design principles that take into consideration the climatic conditions of use, by adjusting dynamic, thermal and energetic simulations used for buildings and their constructional elements to the conditions and types of construction specific to motor homes.

1 MOTOR HOMES

"Motor homes are automobiles with facilities for living. The living area with its equipment must be able to accommodate one or more persons ..." [Road Traffic Licensing Regulations – Germany (StVZO) §19; 20; 21]. Basically, motor homes can be divided into two categories:

- Vans and platform cars

Platform-cars have a living unit fixed to the chassis. They may be divided into three categories:

- alcove vehicles, partly integrated driver's cabin and fully integrated driver's cabin

Figure 1: Campervan Figure 2: Alcove-vehicle

Figure 3: partly integrated driver's cabin
Figure 4: fully integrated driver's cabin

2 MOTOR HOMES IN DIFFERENT CLIMATES

Motor homes care used in varying parts of the world and can thus be exposed to extreme climatic changes, possibly at short intervals. A long holiday in the snowy areas of the Swiss Alps can be followed by a short trip to the warm regions of the Mediterranean Sea or even North Africa.

To date, no studies have been done of the factors involved in optimizing energy behavior and increasing the comfort of motor homes

2.1 Thermal and hygric requirements for a comfortable indoor climate in all-year motor homes

The principal climate parameters which influence a user's climatic perception are air temperature, airflow, relative humidity and temperature of the interior surfaces. All parameters affect the user and are directly connected with one other. Range and limit-values of these parameters with respect to the inside of motor homes are based on accepted measures for comfort as follows:

Air temperature:

- The air temperature should be between 18°C and 22°C.
- On hot days, the air temperature should basically be 3-5 Kelvin lower than the exterior air temperature.
- In order to keep the air circulation at a bearable rate in frequently used areas such as the seating area, ambient temperature should not exceed the air temperature measured at a distance of 200mm from walls and windows by more than 7 Kelvin during the heating phase.
- The difference in air temperature between floor and ceiling should not exceed 3 Kelvin in the main living areas.

Interior surface temperature:

- The interior surface temperatures of the shell should in general not undershoot the inside air temperature by more than 2 Kelvin. This has a positive influence on the perceived air temperature, affected by the radiant temperature of the interior surfaces.
- The surface temperature of the floor may vary between a minimum of 14°C and a maximum of 26°C in order to protect the feet from cooling.
- living areas: approx. 18°C to approx. 22°C
- kitchen: min. 14°C to approx. 22 °C
- bathroom (barefoot area): min. 22°C
- At small elements of the car body shell, such as skylights and windows, additional measures (e.g. a hot-air-outlet) might be needed to raise the interior surface temperature. The same applies for integrated driver cabins.
- Temperatures below dew point should be avoided, as this would lead to condensation on interior surfaces.

Relative humidity:

- In general, a relative air humidity between 30% and 70% has little influence on human comfort and temperature perception. At high humidities, body cooling by perspiration decreases significantly. Too low a humidity will dry out the mucous membranes. The optimal range for relative air humidity thus lies between 18°C/70% and 24°C/40%.

Air flow:

- Strong air flows at normal or low interior temperatures often lead to a local cooling of the body and discomfort. Ideally, the mean air flow should not exceed 0.25m/s
- According to health regulations, an air exchange rate of $0.5 \leq n$ [1/h] ≤ 1.0 must be maintained during winter.
- Due to the air heating systems in motor homes, these values are unrealistically small during the heating-up phase. It is important that the spreading of the hot air to heat up the interior should be fast and regular. Though this will not prevent strong air flows inside the motor home, it ensures that it is *warm* air that circulates inside. Many air vents with small air flow volumes lead to a more even and less turbulent hot air distribution than few large volume vents. On the other hand large vents provide a faster initial heating of the interior. A three-stage set-up according to the following scheme seems to be a reasonable alternative:

  1st stage: Initial heating with maximum heating and ventilation power through few, large-volume outlets in the center of the living area.

  2nd stage: At a certain interior air temperature, the hot air is spread by many outlets and provides an even temperature distribution. The outlets should be located close to the exterior shell in order to heat the surfaces directly.

  3rd stage: Upon reaching a comfortable temperature, ventilation and/or heating should be reduced to a maintenance level. Critical areas, such as an integrated driver cabin, are supplied with increased flows of hot air.

  These statements also apply to air-conditioning systems.

  Design, construction, choice of ventilation, heating and cooling systems in motor homes often lead to these specifications being exceeded.

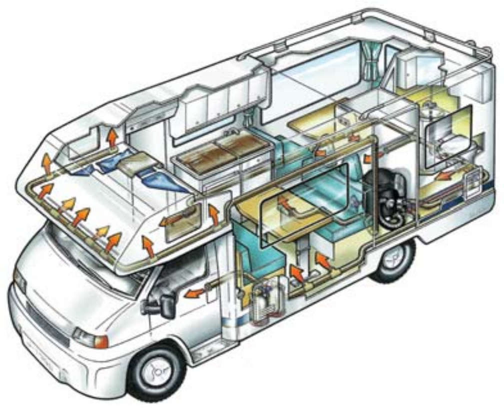

Figure 5: Air distribution system in a motor home

The following problems must be addressed:

- In order to cool down a motor home to the temperature level of a “normal” building at high outdoor temperatures, the energy needed for self-sufficient stand-by operation cannot be supplied economically even by state-of-the-art technology.
- The interior climate changes very rapidly depending on the outdoor climate as a result of the small masses and thicknesses involved compared with buildings. Low heat capacity, relatively poor thermal insulation, etc. also play their part here.
- Because of the predominant use of hot-air heating systems, major turbulences and air flows are unavoidable in order to reduce the energy demand for heating.

Example: different output-temperatures at the vent

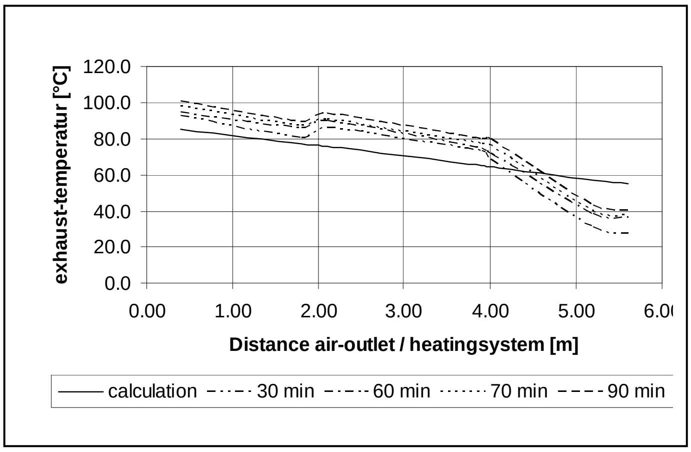

Figure 6: Outlet temperature vs. distance from the heating device

- In DIN EN 1646-1 Annex J clear temperature-differences during heating-up are defined (7 Kelvin).
- The same standard specifies a minimum temperature difference between indoor and outdoor of 35 Kelvin in winter.
- Temperature perception is influenced by the ambient air as well as by the radiant temperature of the surrounding surfaces. The surface temperature of the exterior shell is therefore of decisive importance. It is shown that by increasing the surface temperature (e.g. by good thermal insulation) the indoor air temperature can be decreased, while maintaining the level of comfort.

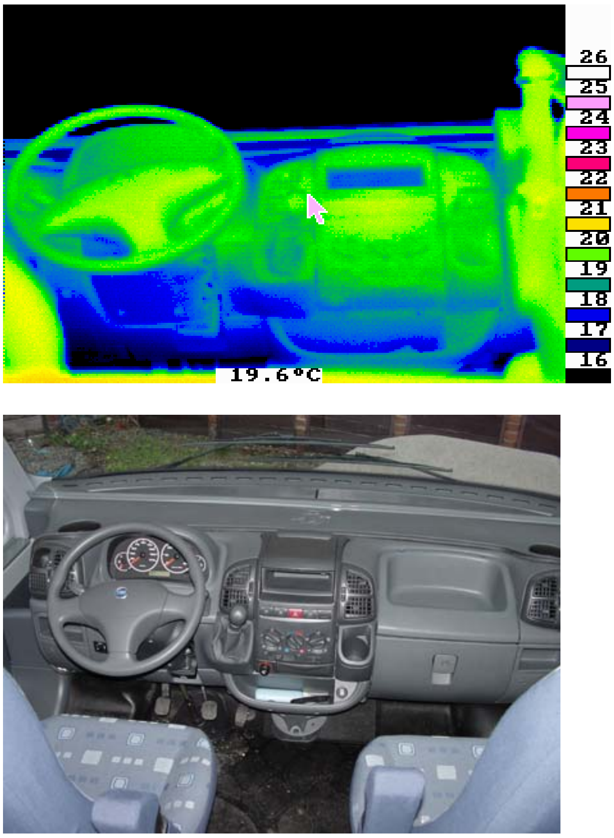

Figure 7: Thermography of the driver's cabin

- Prevention of leakage in order to reduce energy losses and draught

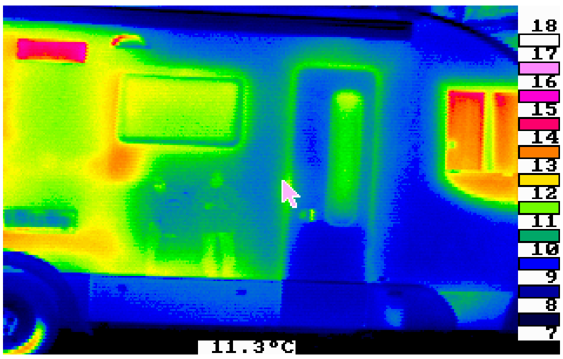

Figure 8: Leakage detected using a Blowerdoor system and thermography for the serial model, car without interior air pressure.

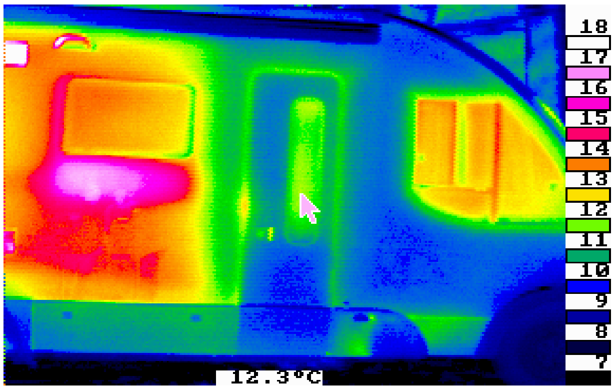

Figure 9: Leakage detected using a Blowerdoor system and thermography, vehicle with constant air pressure of 50 Pascal inside.

- Creation of a comfortable indoor-climate.
- Protection of the construction elements from exposure to climatic moisture.
- All developments in optimizing the climatic performance of motor homes must consider other important factors such as weight reduction, cost minimization, environmental impact and so on.

3 INVESTIGATIONS INTO THE THERMAL-ENERGETIC BEHAVIOR OF MOTOR HOMES AND THE THERMAL-HYGRIC BEHAVIOR OF THE EXTERIOR SHELL

The following tests were conducted. The methods marked * are described in more detail and explained in this publication.

3.1 Building physics construction tests

This investigation focuses on the analysis and evaluation of design and construction methods of motor homes from the point of view of building physics.

3.1.1 Investigations/ evaluations of motor home construction methods

The major task in evaluating the exterior shell construction of motor homes was to analyze the construction components with respect to their layer-design and materials and to transfer the material properties into a database for use with construction physics software.

3.1.2 Investigations/ evaluations of heating, air-conditioning and ventilation systems in motor homes

The main focus was on the analysis of function and operation of different heating, air-conditioning and ventilation systems in motor homes and on processing the data for use in the software systems.

3.1.3 Thermographic study of thermal bridges

Our study of the exterior shell elements focussed the identifying the weak points in the engineering details and connections.

3.1.4 Wind and air tightness of the construction

The construction was tested for leaks using the Blowerdoor method. The air supply louvers were sealed in order to gain information exclusively on the uncontrollable leaks in the shell construction of the motor home.

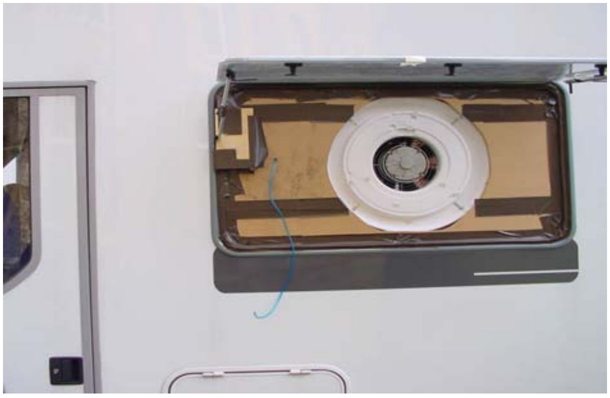

Figure 10: Blowerdoor fan assembly

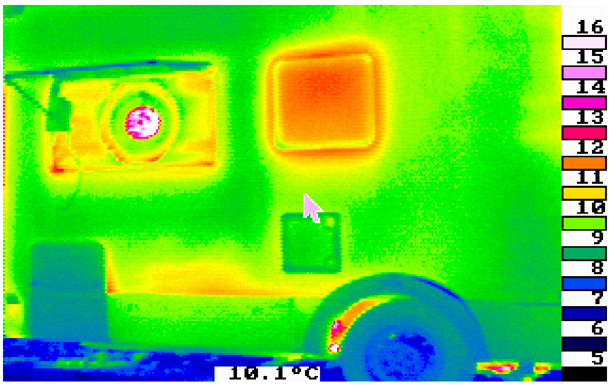

Figure 11: Blowerdoor fan assembly and leak test

3.2 Calculations

One important additional task of the investigation was to test and evaluate the suitability of building physics software for realistic estimations of the thermal-hygric and the thermal-energetic behavior of a motor home and its components taking user and construction specific data into account.
The classification of the numerical methods conforms with applications in recreational vehicle construction:

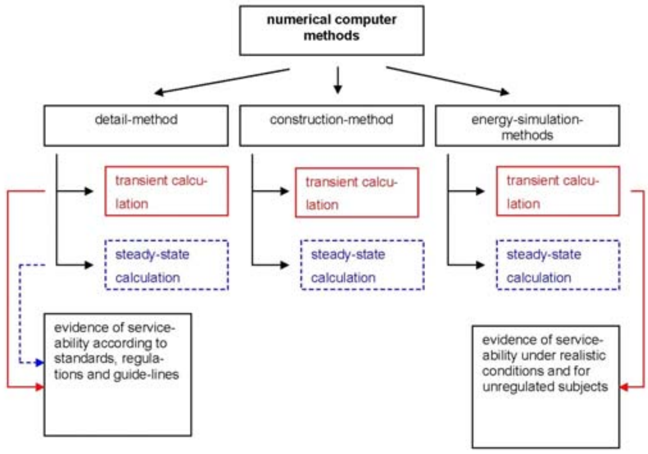

Figure 12: Classification of numerical methods for research on climate in motor homes

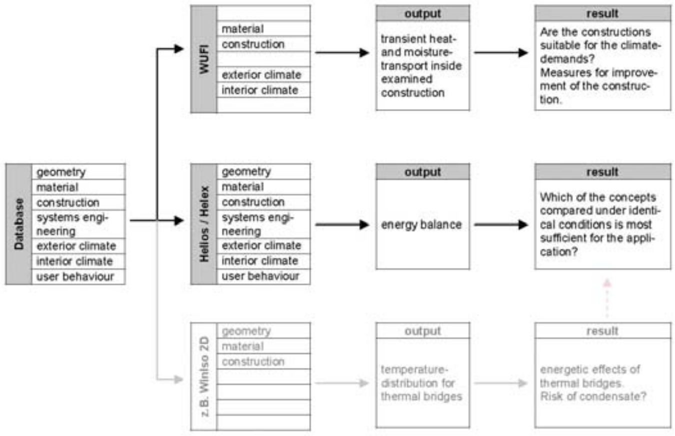

Figure 13: Structure of the software

3.2.1 Investigation into thermal bridges with the software system WinIso 2D

The main tasks in studying construction details with WinIso 2D were:

- Analysis of different thermal weak points
- Cataloguing of thermal bridges and determination of a factor impacting the simulation results.
- Analysis of details with respect to the risk of condensation on the interior surfaces.
- Development of constructive improvements

3.2.2 investigation into the hygrothermal behavior of shell-components with the software system WUFI 3.3*

Major tasks of the investigation of elements of the exterior shell with WUFI (WUFI 1D Version 3.3; IBP Holzkirchen-Germany) were:

- Determination of magnitude and direction of heat-flows through the construction element.
- Determination of magnitude and direction of moisture flows through the construction element.
- To discover if a climate impact will lead to moisture penetration and/or desiccation of the construction element during a specified period.
- From a humidity point of view: Is the construction element able to fulfil requirements in the expected climate?

- Computational comparison and improvement of construction elements and materials of different kinds.
- Determination of borderline situations which lead to a hygric failure of the element.
- Develop measures to optimize construction elements and proof of efficiency of such measures.

3.2.3 *Investigations into the thermal behavior of the motor home with the software system Helios-Helex 2.1 / TRNSYS**

Major tasks of the investigation of motor homes with Helios and Helex 2.1 / TRNSYS* (econzept Energieplanung GmbH–Schweiz / Energy Laboratory of the University of Wisconsin-Madison) were:

- Computation of the air temperatures inside a motor home during a specified simulation period.
- Calculation of the heat transmission losses.
- Determination of the losses due to air exchange.
- Study of the heat storage behavior of the interior construction elements.
- Determination of heat gains due to radiation through transparent elements.
- Determination of performance specifications for heating and cooling systems.
- Comparison and evaluation of various element and vehicle variations under identical conditions.

4 DESCRIPTION OF USER BEHAVIOR AND AMBIENT CLIMATE IN COMPUTER PROGRAMS

The mobility of motor homes and their use for recreation involves changes in outdoor climate and user behavior. Paying regard to these special features we generated specific input data sets for the calculations.

- Data sets for user behavior

These are sets of interior climate, describing the typical behavior of motor home users with respect to the outdoor climate. In order to get as realistic a description as possible, a user poll was carried out to gather the information.

- Data sets for motor home climate

This comprises modified weather data sets, designed to describe the effects of different outdoor climates on the motor home.

- Technical data sets

Additionally, data sets were generated which allow investigation of the energetic and humidity behavior of a motor home under severe conditions or in analogy to defined test-methods (e.g. heating-up test according to DIN EN 1646-1).

5 CONSIDERATION OF THERMAL-HYGRIC BEHAVIOR OF EXTERIOR SHELL ELEMENTS

In order to illustrate an element's moisture behavior, all calculations were made with combinations of different interior air humidities (50% to 80%) and temperatures (5° to 20°C). A basic simulation-cycle of 36 months allowed the long-term study of the construction elements. The climate of the alpine upland region measured at the meteorological station in Holzkirchen, Germany, provided reference data for the outdoor-climate.

Table 1: Overview of results of the serial model

construction element	interior temperature [°C]	Rel. air humidity [%]	Results of the investigation of the serial model
Wall construction, undisturbed	5°C-20°C	50%-80%	Construction and materials are only partially able to fulfill requirements. There are no problems in principle with low interior and high exterior temperatures (e.g. air conditioning). Low outdoor temperatures and interior temperatures above 15°C in combination with long-term air humidities of 70% and higher proved problematic (e.g. in winter-use). Trend: The higher the interior temperature at low outdoor temperatures, the greater the increase of moisture inside the element; the higher the interior air humidity, the greater the moisture-increase inside the element.
Roof construction, undisturbed	5°C-20°C	50%-80%	The roof-construction shows an analogous behavior to the similar wall construction. Construction and materials are able to meet climatic demands only to a limited extent.
Floor construction, undisturbed	5°C-20°C	50%-80%	Construction and materials meet climatic demands well. At normal interior temperatures there are no problems in principle. Due to the vapor barrier in terms of the PVC-floor on the interior side, the interior air humidity is virtually irrelevant. Long periods with interior temperatures below outdoor temperatures must be regarded as potentially problematic (air conditioning in hot regions). Trend: relative air humidity indoors are unimportant. The smaller the temperature difference between indoor and out-

			door, the lower the moisture content of the construction.
Floor construction, driver's cabin	5°C-20°C	50%-80%	Construction and materials are not adequate for climate demands. The same dependencies as for roof and wall-construction apply, but the floor turns out to be more sensitive to high air humidity. Trend: The higher the interior temperature at low outdoor temperatures, the stronger the increase of moisture inside the element. The higher the interior air humidity, the stronger the increase of moisture inside the element.

6 INVESTIGATION INTO THE THERMAL BEHAVIOR OF MOTOR HOMES

The investigations using the software Helios/Trnsys are basically divided into two parts:

- Calculation of heating and cooling energy demand with respect to user behavior and different outdoor climates, including optimization of components, to reduce energy consumption and the associated high costs for heating and/or cooling in Europe.
- Calculation of indoor temperatures in winter and summer with respect to different outdoor climates, including optimization of components, to increase user comfort in motor homes.

Figure 14: Investigated (insulated) indoor area of the motor home

6.1 *Results from the energy examinations*

As a basis for the energy examinations we specified a cold night in winter and the heating-up test according to DIN EN 1646-1. The following alternatives were calculated:

U12-U1closed*:	series model with closed roller blinds
U12-U1open:	series model with open roller blinds
U12-U3*:	Thickness of insulation increased by 10mm in all sandwich constructions (roller blinds closed)
U12-U6*:	Basic air-exchange-ratio decreased from 1,5 to 1 (roller blinds closed)
U12-13:	Combination of the three changes Ux

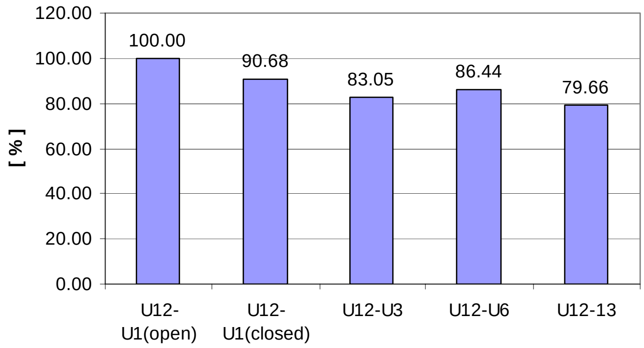

Figure 15: Energy demand for heating against modifications to the vehicle.

As a basis for the energy studies in summer we chose a hot period of several days in southern Europe (in Almeria, Spain). The following alternatives were examined:

U14-U1:	Serial model without any darkening or shading
U15*:	All roller-blinds closed. Shading above 500W/m² radiation. Degree of shading is 90% for all windows.
U15-U3*:	Thickness of insulation increased by 10mm in all sandwich-constructions (roof, walls, floor) (roller blinds closed, shading as U15)
U15-U6*:	Basic air-exchange-ratio decreased from 1,5 to 1 (roller blinds closed, shading as U15)
U16*:	Combination of the three changes Ux described above

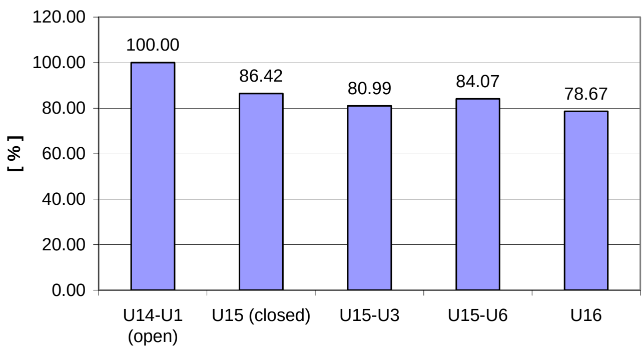

Figure 16: Energy demand for cooling against modifications to the vehicle

The results show that both for heating and for air-conditioning or cooling in summer, the reduction of energy loss due to air exchange is especially desirable along with better insulation of the entire exterior shell. Reducing air exchange by one third saves approximately the same energy as an increase of insulation by 1cm (roof, floor and walls – not the driver's cabin).

6.2 *Temperatures inside a motor home in summer*

For comparison and evaluation purposes, we calculated temperature development inside the motor home in summer without taking air conditioning into account, in order to show the climatic influence of the variables. A calculation with air-conditioning would fail to demonstrate dependencies. The data sets for motor home climate and user behavior served as a basis for our calculations.

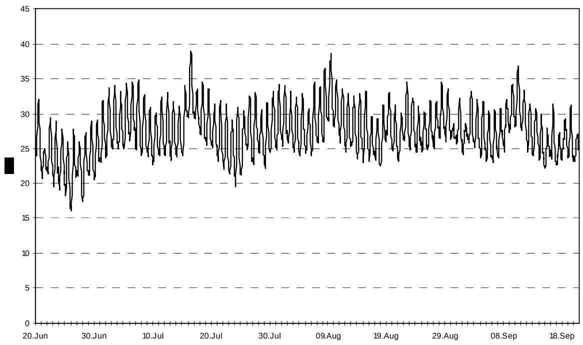

Figure 17: Outdoor temperature during calculation-period in winter – Almeria, Spain

6.2.1 *Climate during summer-period – Almeria, Spain*

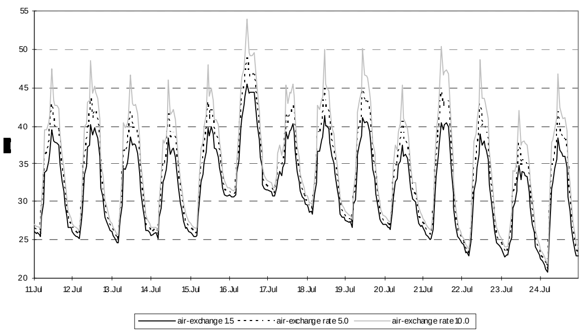

Figure 18: indoor temperatures against air-exchange-ratio(AER); AER = 1,5 – blue; AER = 5,0 – gray; AER = 10,0 – red; outdoor temperature – black

The calculations for the temperature behavior under summer conditions show the following results for Almeria, Spain:

- Increase of insulation thickness has almost no influence on indoor temperatures in motor homes. Caravan users often remark that a thicker insulation layer worsens the summer indoor climate ("barrack-climate"). This could not be confirmed.
- Indoor temperatures can be decreased by means of controlled shading of the large transparent building elements.
- Decrease of indoor temperatures can be achieved by a high air-exchange-ratio.
- In all cases studied, the indoor temperatures develop in line with the outdoor temperature. Due to the low heat storage capacity, it is not possible to smooth the temperature peaks.
- With current technology, on hot summer days, indoor temperatures can not be brought under outdoor temperature without use of air-conditioning.
- Pursuing further the investigations described here can help to establish characteristic diagrams for the control of ventilation and shading, among other things.
- Furthermore, to save energy in midsummer, before using air conditioning, the interior should be ventilated to lower indoor temperatures.

6.3 *Temperatures inside a motor home in winter*

To evaluate the influences of the outdoor climate more precisely, the calculations were carried out without taking any heating system into account, in order to show the climatic influence of the variables. A calculation with heating would fail to demonstrate dependencies. The data-sets for motor home climate and user behavior served as a basis for our calculations.

To obtain a clear overview of the calculated variables, a period with low and relatively constant temperatures between January 26th and February 8th was chosen.

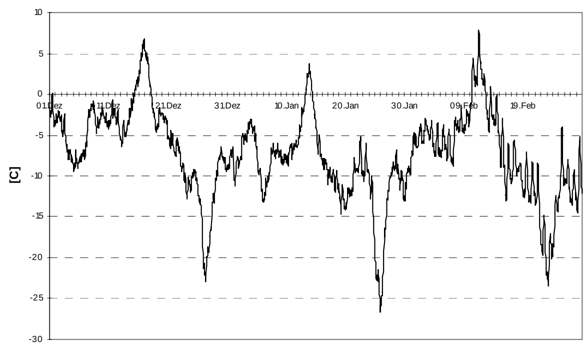

Figure 19: Outdoor-temperature during winter – Moscow, Russia

6.3.1 *Climate during winter-period Moscow/Russia*

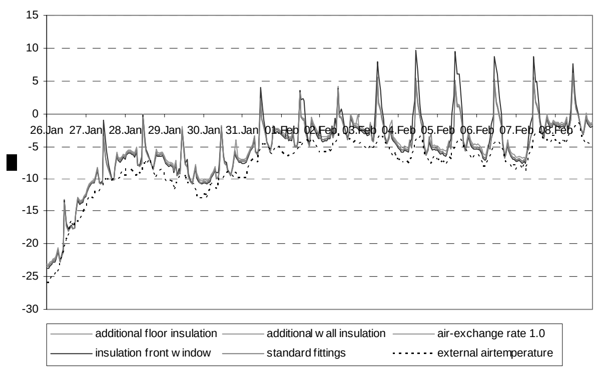

Figure 20: indoor-temperatures against thermal resistance of exterior shell elements

The calculations for the temperature behavior under summer conditions show the following results for Moscow, Russia:

- Additional thermal insulation is most effective on elements with broad surfaces and those with poor thermal properties.
- Improving the thermal insulation of the body is of little use unless the poor insulation of the windscreen is addressed.
- Thermal upgrade of the transparent elements is necessary, but their energy transmission should not be reduced.
- A controlled glare shield with good thermal insulation represents the optimal solution. On the one hand, heat loss via transparent elements can be minimized by closing the glare shield at night, while an open glare screen on sunny winter days brings solar radiation to the interior of the motor home.

7 SUMMARY

The calculations shown in this paper illustrate only an extract from investigations into climate in motor homes which were conducted within the scope of a research program at the University of Applied Sciences and Arts, HAWK Hildesheim, Germany.

As a result of these investigations, it appears that varying user behavior as well as regional climates are of decisive importance for the indoor climate and the construction elements of motor homes. There are, however, universal rules and basic principles for development and evaluation of motor homes.

The following investigations could help to amplify the results:

- Practical investigations of climate in motor homes.
- Exact numerical evaluation of these investigations.
- Study of real damage and claims due to inadequate climate suitability of construction elements.
- Research into air-conditioning.
- Exact determination of the material characteristics needed for computer simulations.
- A study of cooling and heating behavior in summer and winter.
- Exact determination of temperature development during a heating-up test according to DIN EN 1646-1 *.

Gathering of data regarding long term indoor-temperature development (e.g. over 36 months) and integration of these values in the indoor climate presentation of the software WUFI.

8 INDEX OF SOURCES

8.1 Literature, norms, guidelines

[1] Straßenverkehrszulassungsordnung (STVZO) §19; 20; 21

[2] DIN EN 721 – Anforderungen an die Zwangsbelüftung

[3] DIN EN 1646-1

[4] Zeitschrift promobil 4/2003

[] H. Arndt; Wärmeschutz und Feuchte in der Praxis; Verlag Bauwesen Berlin; ISBN 3-345-00800-9

[6] Physik in Übersichten; Volkseigener Verlag Berlin Volk und Wissen; ISBN nicht vorhanden

[7] Hilfetexte von WUFI; IBP Holzkirchen

[8] Gertis; Sonnenenergie und Wärmepumpe; Heft 5/1983

[9] N.I.T. Institut für Bäderforschung und Tourismus

[10] N. Gruler, F. Stein; Sonnenschutz leicht gemacht

[11] Prof. Dr.-Ing. Hans-Peter Leimer; Vorlesungsskripte zur Bauphysik der FH Hildesheim

[12] Zukunftsinitiative Bau; Landesinitiative für Bauwesen des Landes NRW

8.2 Software used

[1] WUFI 1D Version 3.3; IBP Holzkirchen (Thermisch - Hygrische Bauteilsimulationen)

[2] Helios und Helex 2.1; econzept Energieplanung GmbH (Energetische Simulationen)

[3] TRNSYS, Version 15.3.00 Solar Energy Laboratory University of Wisconsin-Madison, (Thermisch-Hygrische Simulationen)

[4] WinIso 2D (Thermische Bauteilsimulationen)