

Thermophysical Properties Measurement of Interior Car Materials vs. Temperature and Mechanical Compression

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ABSTRACT

Thermophysical properties of materials used in the design of automotive interiors are needed for computer simulation of climate conditions inside the vehicle. These properties are required for assessment of the vehicle occupants' thermal sensation as they come in contact with the vehicle interior components, such as steering wheels, arm rests, instruments panel and seats.

This paper presents the results of an investigation into the thermophysical properties of materials which are required for solving the non-linear Fourier equations with any boundary conditions and taking into account materials' specific heat, volume density, thermal conductivity, and thermal optical properties (spectral and total emissivity and absorptivity). The model and results of the computer simulation will be published in a separate paper.

The tested materials included foam, leather/foam laminated materials, and a few plastic laminated materials, which were used in the construction of various automotive interior parts. One original aspect of this work was the testing of plastic foam samples both at a wide temperature range from -20°C to $+60^{\circ}\text{C}$ and at varying compression levels up to 60%. Such data is needed for calculation of heat conduction within occupied automotive seats which are undergoing different static and dynamic loads.

Thermal conductivity was determined as the product of thermal diffusivity and volume specific heat. The thermal diffusivity was measured in accordance to ASTM STP 1320, and the specific heat was measured according to ASTM E1269, both in the temperature range from -20°C to $+60^{\circ}\text{C}$. The emissivity and absorptivity were measured according to ASTM E408 and ASTM E903, respectively at room temperature.

The new experimental data obtained has scientific and practical interests for thermal science and engineering applications. The thermal conductivity results of the foam materials in the wide range of temperatures and compression/deformation are of interest for the development of heat transfer mechanisms in porous media, for materials science and technology. All data together enable the development of advanced mathematical models for the design, assessment and optimization of climate conditions inside cars and other vehicles.

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INTRODUCTION

Modern design and optimization of climate control inside transportation vehicles is based on computer simulation of heat and mass transfer under different environmental conditions. The materials that comprise the typical automotive seat are

undergoing static and dynamic mechanical loading with reversible deformation. Ford & ESI are developing non-linear mathematical models and software which allow predictive simulation of these processes. The measurements of thermophysical properties requested for this model were carried out at Integrity Testing Labs Inc (Ontario, Canada).

Heat transfer and climate conditions, including tactile senses of people during contacts with seat, are determined by thermophysical properties of the materials used. The aim of the work described in this paper is to provide thermophysical properties of the car interior materials to enable such a mathematical model: thermal conductivity, specific heat, volume density, thermal optical properties. Some of the data, particularly the ones obtained during compression and wide temperature range, has large scientific interest for thermal science and material science:

- heat transfer in porous media under its deformation;
- analyses of different factors which influence the combined heat and mass transfer during conduction, convection, and heat radiation;
- material science and technology of heat insulation materials and elastomers;

The developed test methods for thermal conductivity and diffusivity and their modifications can be used and have been used for other classes of compressible materials: ceramic fibers [1], polymer electrolyte membrane (PEM) fuel cells [2], elastomers, etc.

MATERIAL SPECIMENS

All specimens submitted for material characterization are used in automotive interiors and can be divided into two groups.

- Materials which do not undergo significant deformation: Instrument Panel (Sample #1), Upper Door Trim (Sample #2), Lower Door Trim (Sample #3), Headliner (Sample #4), and Carpet (Sample #5).
- Materials which undergo mechanical compression and deformation: Polyurethane foam for Back Cushion (Sample #6) and Seat Cushion (Sample #7).

TESTING BY STANDARD METHODS

[Table 1](#) presents the general description of the tested samples including a summary of the averaged properties as measured by standard methods. A full sized view of [Table 1](#) is also presented in the [Appendix](#).

While there exists interest regarding the thermomechanical properties all of these materials typically used in an automotive interior, the results of which are not detailed further than the summary shown in [Table 1](#). This by no means discounts the value or challenge in studying these materials but rather provides a forum to discuss the unique challenges associated with the seat foams currently used industry wide. The following discussion provides abbreviated details about the standard test methods used.

Table 1. Summary of the materials properties measured by standard methods *

#	Common Name	General Description	Density kg/m^3	Specific Heat vs. $T, ^\circ\text{C}$ J/kgK	Optical properties		
					Surface	Solar Abs.	I.R. Emit.
1	Instrumental Panel	Laminated: flexible rough synthetic leather 1.5mm, foam 7mm, plastic 3.7mm	390	$6.638T + 1367$	Black synthetic Leather	0.960	0.923
2	Upper Door Trim	Laminated: flexible smooth synthetic leather 0.7mm, foam 7mm, plastic 3.7mm	400	$-0.0214T^2 + 6.57T + 1335$	Black Leather	0.938	0.916
3	Lower Door Trim	Plastic 3 mm	850	$0.00242T^2 + 7.25T + 1258$	Grey Plastic	0.730	0.924
4	Headliner	Laminated: fabric 0.5 mm, non-woven material 1 mm, foam 6.5 mm, non-woven material 1 mm	210	$0.03854T^2 + 5.35T + 999$	Yellow fabric	0.315	0.854
5	Carpet	Laminated: no-woven material 3mm, non-woven material 4 mm, foam 2 mm	198	$0.00669T^2 + 7.60T + 844$	Black non-woven	0.944	0.898
6	Back Cushion Foam PU	Thick polyurethane foam	62	$0.0324T^2 + 4.63T + 1225$	Yellow foam	0.180	0.901
7	Seat Cushion Foam PU	Thick polyurethane foam	62	$0.02287T^2 + 4.207T + 1294$	Yellow foam	0.163	0.894

***Note:** The composition and structure of the sample in general description is qualitative.

The volume density, ρ , was measured at room temperature according to ASTM C 302 as the ratio of the mass of the specimen to its volume. Taking into account possible non-uniformity in the shape of the surface, we estimated the error of the volume density measurement to be 2-3 %.

The specific heat was measured in accordance with the ASTM E 1269 "Standard Test Method for Determining Specific Heat Capacity by Differential Scanning Calorimetry". The measurements were performed using a TA Instruments, Model Type Q10 DSC. The estimated measurement error was around 3-5%.

The solar absorptance (α_s) measurement was performed in accordance with ASTM E 903. The total reflectance measurement was performed with a dual beam, ratio recording Beckman DK-2A UV-VIS-IR spectrophotometer. The instrument recorded reflectance data from 350 nm to 2450 nm as a percentage of a working standard's reflectance. Solar absorptance was then calculated using the 50-point selected ordinate method per ASTM E 903. The wavelengths for the 50 selected ordinates used are provided in ASTM E 891. The estimated measurement error was around 5-8 %.

Total normal infrared emittance (ϵ) measurements were performed in accordance with ASTM E 408, Method A. A Gier Dunkle Instruments Infrared Reflectometer Model DB 100 was employed for the infrared reflectance measurements.

This instrument gives a single integrated value over the wavelength region from 5 to 25 micrometers. The obtained reflectance data was used to calculate the infrared emittance using Kirchhoff's Relationship. The estimated measurement error was around 5-7%.

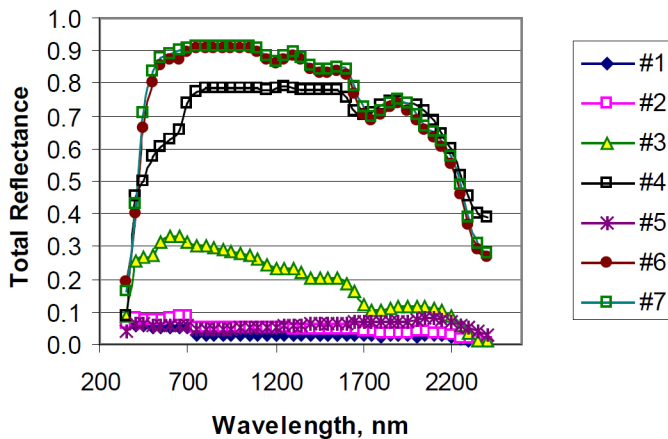


Figure 1. Total Reflectance vs Wavelength for the samples #1- #7

One can see in Table 1 that there is a correlation between color of the materials in the visible part of spectrum and solar absorption and reflection. The black color materials #1, #2, #5 has solar absorptance of 0.94-0.96; the grey material #3 has absorptance of 0.73; the yellow materials #4, #6, #7 have solar absorptance in the range of 0.16-0.32. A possible reason of this correlation is that optical properties are connected with content of carbon in the materials. In general, the hypothesis is that the higher the carbon content, the darker the material which results in higher the solar absorptance.

An interesting result is that the highly porous polyurethane foam materials #6 and #7 have low solar absorptance (0.16-0.18) and high emittance (0.89-0.90). Similar phenomenon was noted by V. Issoupov [3] in modern roofing materials. Evidently mechanisms of apparent absorptance and emittance of radiation for these porous materials are different. The solar absorptance and reflectance are determined by materials composition. High thermal emittance of foam materials is caused by their porous structure and cellular surface pores can have high emittance close to that of a black body cavity.

INFLUENCE OF MECHANICAL COMPRESSION AND TEMPERATURE ON THERMAL CONDUCTIVITY

The initial density of automotive interior materials used in seat cushions and back rests will change under the application of a compression force caused by the passenger's weight; therefore, their porous microstructures vary with the applied force. The understanding of the microstructure state in applied engineering processes is very complicated and only experiment can provide reliable information about the influence of mechanical compression on the apparent thermal conductivity and diffusivity.

Thermal conductivity of thin layers of porous materials based on ceramics and carbon fibers were measured under mechanical compression using modified slag calorimeter method [1-2]. However, in the present case, the samples of seat foam were thick and temperature differences in the

samples were too large that made it difficult to correctly apply the slag calorimeter method. Therefore, a special testing method & technique was developed for thermal conductivity and thermal diffusivity measurements. This effort was of such materials in order to obtain reliable reference data on their thermophysical properties under compression.

This study has delivered the following major tasks:

- Development of a test method for measurement of thermal diffusivity and thermal conductivity in a wide temperature range and at different compression forces.
- Studying the automotive interior insulative thermal-physical properties in a temperature range from -20°C to +60°C and at four different mechanical compression values under uniform deformation of 0%, 20%, 40%, and 60%.

Measurement Methodology

The thermal conductivity, λ , was determined as the product:

$$\lambda = \alpha \times c \times \rho \quad (1)$$

where ρ is the volume density and, c is the specific heat of the specimen, and α is the thermal diffusivity.

We used standard ASTM methods to determine specific heat and volume density (see previous Section). The apparent thermal diffusivity, α_{app} , was measured using the monotonous heating method based on the Fourier equation and originally described in [4, 5, 6, 7, 8]. The apparent thermal diffusivity was determined using Eq. (2) by measuring the heating rate and the average temperature difference between thermocouples placed at a distance $\pm L$ from the center (near the surfaces of the specimen) and at the center of the specimen.

Using the "small temperature differences" approach and a quasi-constant heating rate $b = dT/dt$, we obtained the following expression for the apparent thermal diffusivity:

$$\alpha_{app} = (b L^2 / 2\nu)(1 + \Delta_1 + \Delta_2) \quad (2)$$

Here ν is the temperature difference between the points with coordinates L of the thermocouple (usually near the surfaces and near the center). The Δ_1 term is the correction on non-linearity of the Fourier equations and Δ_2 is the correction on non-dimensionally of the temperature field. The corrections Δ_1 and Δ_2 can be estimated analytically [4, 5, 6].

The measurement error of the thermal diffusivity was about 3-5 %. The main origin of the error could be attributed to the measurement of temperature differences in the specimens and to the distance between the center of the sample and surface thermocouples.