# 이상물질의 열전도도에 대한 연구

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# A study on the thermal conductivity of two-phase material

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## 1. Introduction

### 1.1. Reaction Injection Molding

Reaction Injection Molding (RIM) is a method for production of complex plastic parts from monomers or oligomers. Since 1970, it has been used as the important process for molding large polyurethane automotive parts. But today, with the advent of other RIM materials, followed by the technique of an internal mold release (IMR) that reduces cycle time, RIM has become one of the major methods of processing

Polyurethane foam is produced according to decomposition of blowing agent that is mixed with reactant in advance. Polyurethane foam generally has low mechanical properties, but it has many advantages such as low weight, saving of material, improved impact strength, and lowered thermal conductivity. Chemical blowing agents react with isocyanate to form gas, which forms bubble structure. Physical blowing agents form bubbles through decompression of condensed gas or evaporation of liquid.

### 1.2. Microcellular Foam

Microcellular foam is polymeric foam with cell sizes on the order of 10 microns in diameter. It was originally developed at the Massachusetts Institute of Technology in the early 1980s to reduce the materials consumption and to increase the toughness of materials. Microcellular foams represent very high impact strength as compared to unfoamed plastics. The small cell size allows foaming of very thin sections. Microcellular foams also have increased thermal and electrical insulation properties, high toughness, high stiffness-to-weight ratio, and high fatigue life. All of these advantages can be obtained while reducing the cost of materials and the weight of the product.

In this study, polyurethane foams are produced by reaction injection molding and microcellular high impact polystyrene (HIPS) foams are produced. The procedures for producing foams are also described. Polyurethane foams and HIPS foams are then mixed to form a hybrid foam. Thermal conductivity models for two-phase material are examined. Thermal conductivities of polyurethane foams, HIPS foams, and hybrid foams are measured experimentally and compared with theoretical values.

## 2. Theory

A large number of theoretical and empirical models to estimate effective thermal conductivity of the two-phase material have been proposed. Parallel, series, geometric mean, CPS (cubic-parallel-series), CSP (cubic-series-parallel), Maxwell, Brailsford, Cheng and Vachon's Model are used in this study.

## 3. Experiments

### 3.1. HIPS Microcellular Foam

The first step of making microcellular foam was saturating solid-state HIPS with carbon dioxide at the pressure of 0.3 MPa. The saturating time was 48 hours. When the beads of HIPS were taken out from the pressure vessel, they were in the state of supersaturation. Then, the supersaturated HIPS were submerged under silicon oil which had been heated to the chosen temperature in advance. Because all foaming temperatures were slightly above glass transition temperature of HIPS, carbon dioxide supersaturated in HIPS expand itself to form foam structure. However, due to the limited growth of the nucleated cells, we could obtain the microcells the size of which are under 100 microns in diameter.

### 3.2. Hybrid Foam Consisting of Two-foamed Material

Hybrid foams consisting of two-foamed materials were made. Fig. 1 shows the installation of mold for producing the composite. The wire-net was placed inside the mold and a number of beads of foamed HIPS put in the installed wire-net. Then, the impingement-mixed polyurethane was injected inward. At the early stage, polyurethane foam filled up the free space rather than the inside of wire-net because of the flow resistance of the dense HIPS beads. After filling all the free space, polyurethane foam began to permeate through the HIPS beads. Polyurethane foam filled all small gaps among the HIPS and a hybrid foam consisting of two-foamed materials (HIPS and polyurethane) was finally produced.

## 4. Results and Discussion

### 4.1. Results of HIPS Microcellular Foam

In Fig. 2 two micrographs of the foamed HIPS samples are shown. The effect of the foaming time on the thermal conductivity can be also found in Fig. 3. The thermal conductivity decreases as increasing of the foaming time. Fig. 4 shows the effect of the foaming temperature on the thermal conductivity. At low temperature, because it takes long time until the beads of HIPS are fully foamed, the gas diffuses out of HIPS slowly for long time. Consequently, little gas contributes to growth of the cells and the density is relatively high. As the foaming temperature rises, more gas contributes to growth of the cells so that the density is the lowest at the temperature of 130°C. However, at the temperature higher than 130°C, the diffusivity of the gas gets higher and much gas diffuses out of HIPS before it contributes to foaming. That is why the density increases above the temperature of 130°C.

### 4.2. Thermal Conductivity of Hybrid Foam

Assuming that the air replaces all the carbon dioxide gas inside the HIPS foam, the comparison between newly predicted values and the measured value is shown in Fig. 5. The thermal conductivities considering the aging effect slightly overestimate the experimental value. Practically, the gas inside the bubbles is the mixture of carbon dioxide and the air, so that the exact estimation of the thermal conductivity is below the value in Fig. 4.17. Consequently, the thermal conductivities predicted by various models fit the experimental result quite well.

## 5. Conclusions

By heating HIPS beads supersaturated with carbon dioxide, the microcellular foam structure is obtained. Effects of processing conditions on the foam structure are inspected with SEM micrographs. The density and the thermal conductivity decrease fast with foaming time at the beginning. The rate of decrease is reduced with foaming time. The minimum density and thermal conductivity are also obtained at foaming temperature of 130°C.

Polyurethane foam is produced by reaction injection molding and the hybrid foam consisting of HIPS microcellular foam and polyurethane foam was made. Various models predicting the thermal conductivity of two-phase material give values similar to the experimental result. Nielsen's model predicts higher value than the upper bound and is not applicable to this system. The measured thermal conductivity is almost equal to that predicted by parallel model. The theoretical values by other models slightly underestimate the measured thermal conductivity. If aging effect is taken into consideration, the thermal conductivities predicted by various models fit the experimental result well.

## 6. Acknowledgement

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## 7. References

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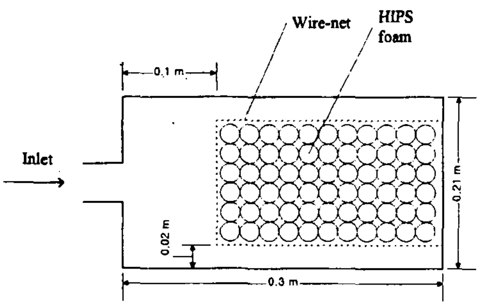
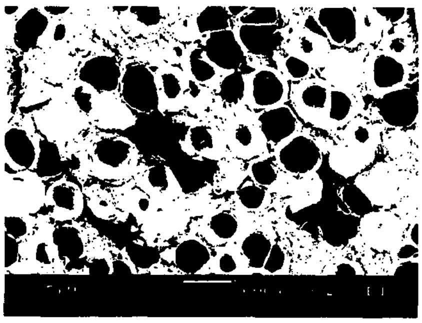
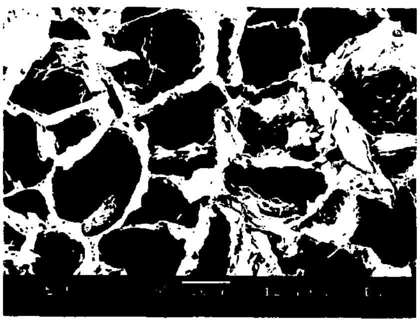



Fig. 1. Installation of mold for producing the composite.



(a)



(b)

Fig. 2. SEM micrographs of the HIPS foam produced in the condition of (a) foaming temperature: 130°C, foaming time: 10s. (b) foaming temperature: 130°C, foaming time: 60s.

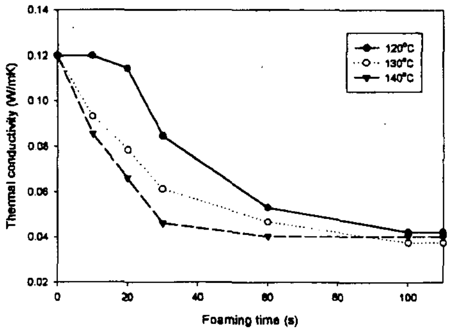



Fig. 3. Effect of foaming time on the thermal conductivity.

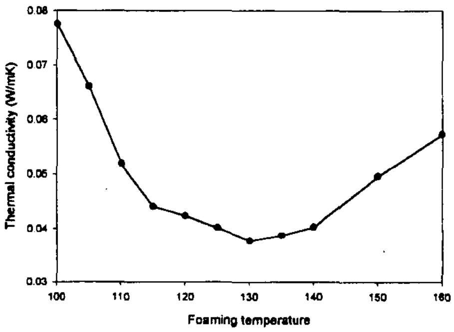



Fig. 4. Effect of foaming temperature on the thermal conductivity: foaming time is 600s for all samples.

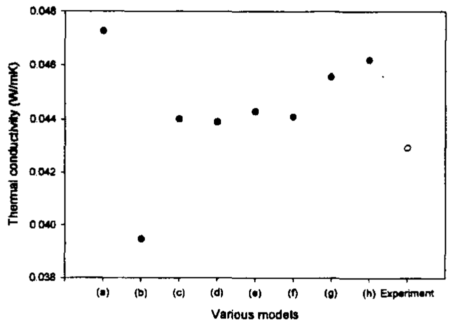



Fig. 5. Thermal conductivities of the hybrid foam predicted by various models assuming that carbon dioxide inside HIPS foam is replaced by air. (a) parallel; (b) series; (c) geometric mean; (d) CSP; (e) CPS; (f) Maxwell; (g) Brailsford; (h) Cheng and Vachon