

# **Boundary Conditions in the Modeling of Heat Exchangers**

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## **Summary:**

The possibility of building heat exchangers from plastic will be discussed in this paper. Possibilities for the modeling of the heat transfer and some conditions associated with those exchangers going in to production are first conceived, then discussed, and finally compared to the achieved actual worth of those devices already in use.

## **Keywords:**

Heat Exchanger, heat transfer, heat exchange

## 1. Introduction

Heat exchangers are at the heart of many technical devices. For this important reason, they should be generally fashioned in accordance with optimal availability and with regard to their grade of effectiveness. For the same reason the production costs of a heat exchanger should be minimized. Up to now all heat exchangers were made of metal, namely copper or aluminum because of the good heat conductivity. But these materials are expensive and the production is intensive.

So the question arises – at first glance a stupid one – why does no one make heat exchangers out of plastic? It is cheap, easy to produce, less weight, costs less overall.

If one takes this question seriously, one has to have a closer look in what capacity heat transferring mechanisms like diffusion, convection and radiation are relevant, and moreover, which important part simulation technology has to play in the realization of such an unusual device.

Introduced here is the first heat exchanger used in household appliances made of plastic. Different possibilities for the modeling of the heat transfer, and some conditions associated with those exchangers going in to production are conceived, discussed, and finally compared to the achieved actual worth of those devices already in use.

## 2. Heat transfer mechanisms and dominating factors

In general, heat can only be transferred by one of the two following mechanisms:

- contact
- radiation

According to the temperature range in which household appliances normally operate, the effect of radiation can be neglected. So the only mechanism remaining is contact.

To figure out the restricting factors which, until now, have prevented people from constructing heat exchangers from materials other than metal, recall the (empirical) equation which governs the heat exchange between two regions of different temperatures divided by an intermediate material:

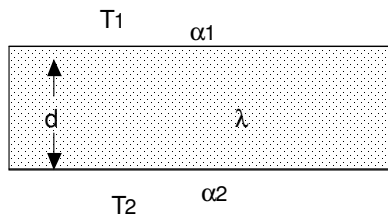


Fig.1: Heat exchange through plane walls

The heat exchange is given [1] by

$$\dot{Q} = k A \Delta T \quad (1)$$

with

$$k = \frac{1}{\frac{1}{\alpha_1} + \frac{d}{\lambda} + \frac{1}{\alpha_2}} \quad (2)$$

The relevant parameters determining the heat transfer are:

$\lambda$  : heat exchange coefficient

$\alpha_1, \alpha_2$  : heat transfer coefficient at the two surfaces

d: thickness of the intermediate material

A: area of contact

$\Delta T$  : temperature difference

Table 1: Typical values for heat exchange parameters

| $\alpha_1$ (W/m <sup>2</sup> K) | $\alpha_2$ (W/m <sup>2</sup> K) | $\lambda_{\text{alu}}$ (W/mK) | $\lambda_{\text{plastic}}$ (W/mK) |
|---------------------------------|---------------------------------|-------------------------------|-----------------------------------|
| 50                              | 500                             | 215                           | 0.2                               |

Inserting the typical values of these parameters (Tab.1) into eqs. (1) and (2), the heat exchange coefficient for a given thickness of  $d=2$  mm is calculated to:

$k = 45.5$  W/m<sup>2</sup>K for aluminum and  $k = 27$  W/m<sup>2</sup>K for plastic, which is almost half compared to aluminum.

However, reducing the thickness by a factor of ten, which can be easily done to plastic without losing too much mechanical stability (stiffness), results in a heat exchange coefficient for plastic of  $k = 43.5$  W/m<sup>2</sup>K, which is now nearly the same as that of aluminum.

In this case, the transfer of heat through the intermediate material does not play a major role any more, causing the surface heat transfer to become the dominating factor.

### 3. Heat transfer at the boundaries

There are in general, two approaches to calculate the heat transfer quantitatively.

#### 3.1 The empirical approach

This approach is mostly used in engineering applications, although it is more empirical than theoretical. By introducing an empirical heat transfer coefficient  $\alpha$  in the following scheme,

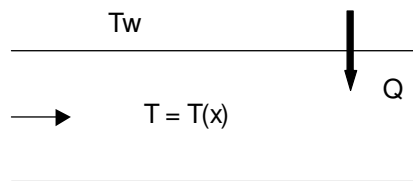


Fig.2: Heat transfer through a surface

the heat transfer is given by

$$\dot{Q} = \alpha ( T - T_w ) \quad (3)$$

$T_w$  is the temperature at the wall,  $T$  is an average (bulk) temperature of the fluid (which varies downstream with  $x$ ,  $T = T(x)$ ) and  $\alpha$  is the heat transfer coefficient. It is important to note that this approach does not explicitly take into account a detailed variation of the fluid temperature with the normal coordinate  $y$ .

#### 3.2 The direct approach

This approach relates to the principle fact, that heat can only be transferred through contact (ignoring radiation effects). That means that, in the laminar case, we 'simply' have only to solve the (coupled) differential equations which govern the momentum and energy transport in the cooling fluid (with density  $\rho$ , specific heat  $c_p$ , viscosity  $\nu$  and heat conductivity  $\kappa$ ). These equations are:

i.) the Navier-Stokes-equation

$$\partial_i u_i + u_j \partial_j u_i - \nu \partial_j \partial_j u_i = - \frac{1}{\rho} \partial_i P \quad (4)$$

and

ii.) the energy equation

$$\rho c_p [\partial_t T + u_j \partial_j T] - \kappa \partial_j \partial_j T = 0 \quad (5)$$

In this case the following boundary conditions are valid:  
 At the inlet: fixed values of the velocity  $u_{inlet} = \text{const}$  and temperature  $T = T_{inlet}$   
 At the wall: fixed values of the velocity  $u_{wall} = 0$  and temperature  $T = T_{wall}$

#### 4. The reference heat exchanger

Which of the previous approaches is more appropriate for the design of a new generation of heat exchangers was answered by comparing the results from each approach with the experimental data derived from a reference heat exchanger. This exchanger consists simply of two parallel planes made of plastic. The results are shown in the figures below and in table 2:

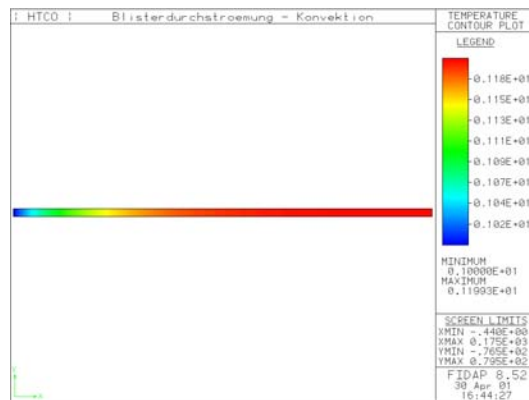


Fig. 2: Temperature distribution – empirical

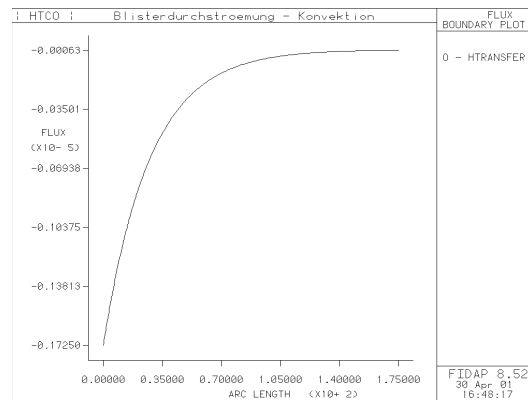


Fig. 4: Heat transfer - empirical

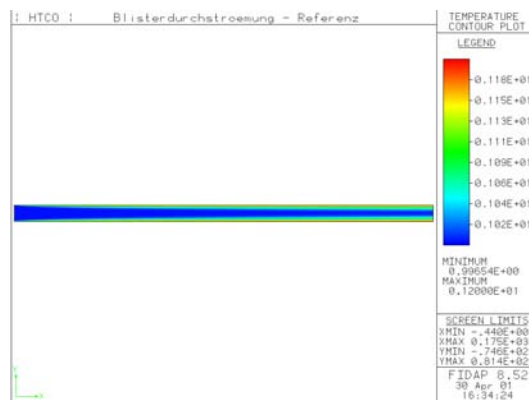


Fig. 3: Temperature distribution - direct

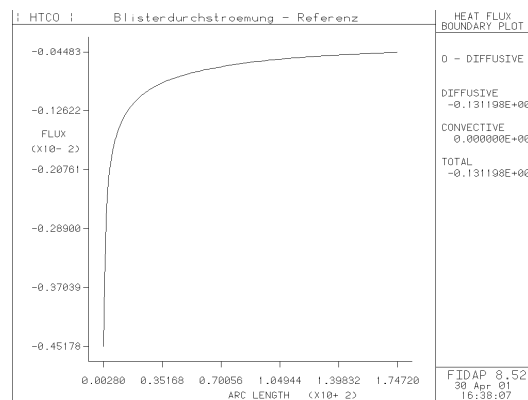


Fig. 5: Heat transfer – direct

Table 2: results of the reference heat exchanger

| Heat  | experimental | empirical | direct |
|-------|--------------|-----------|--------|
| Q (W) | 146          | 40        | 133    |

## 5. Details of the direct modeling

According to these results (and anticipating more complex geometrical structures for the heat exchanger) the direct approach was applied for further research studies for a new type of heat exchanger. The modeling and simulation was carried out in a non-dimensional fashion  $u_i = u_0 u_i^*$ ,  $T = T_0 T^*$  (for convenience the asterisks are omitted again in the following). The equations for the stationary case then read:

$$u_j \partial_j u_i - \text{Re}^{-1} \partial_j \partial_j u_i = -\partial_i P \quad (6)$$

and

$$u_j \partial_j T - \kappa^* \partial_j \partial_j T = 0 \quad (7)$$

The parameters used in this simulation are shown below (table 3).

Table 3: Model parameters

| $\rho$ (kg/m <sup>3</sup> ) | $\nu$ (mm <sup>2</sup> /s) | $c_p$ (J/kgK) | $\kappa$ (W/Km) | $u_0$ (m/s) | $T_0$ (K) | Re  | $\kappa^*$ |
|-----------------------------|----------------------------|---------------|-----------------|-------------|-----------|-----|------------|
| 1.2                         | 15.1                       | 1.02e3        | 2.57e-2         | 4.763       | 293       | 315 | 4.433e-3   |

## 6. New types of heat exchangers

Recalling Eq. (1), there is another parameter which increases the heat transfer rate, namely the area of heat exchange. This factor makes the use of plastic heat exchangers virtually unrestricted because of the flexibility plastic has to offer. Using techniques like molding for example, creating any shape with almost any surface area becomes possible. Thus, in order to increase the acting area for the heat exchange, the following shapes were considered:



Fig. 6a: shape 1



Fig. 6b: shape 2



Fig. 6c: shape 3



Fig. 6d: shape 4

## 7. A realized plastic heat exchanger

The heat transferring ability of all the shapes sketched in Fig. 6 were calculated by CFD (see chapter 5). It turned out that the crucial factor for the best heat transfer is an optimal motion of the fluid.

Taking into account further restrictions, like overall size, total pressure loss in the whole device, etc., which are imposed by the operation conditions of heat exchangers in daily use, the shape Fig. 6d (shape 4) was finally realized.

Detailed results of the simulation are shown in the following:

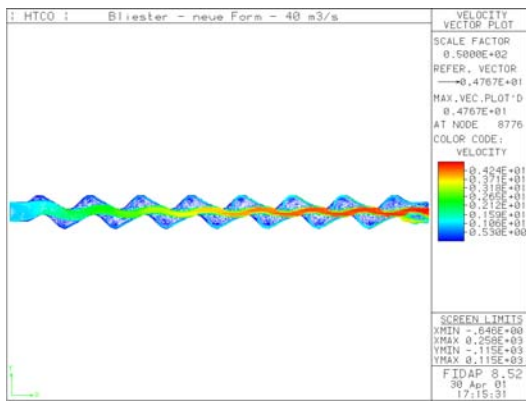


Fig.7 Velocity

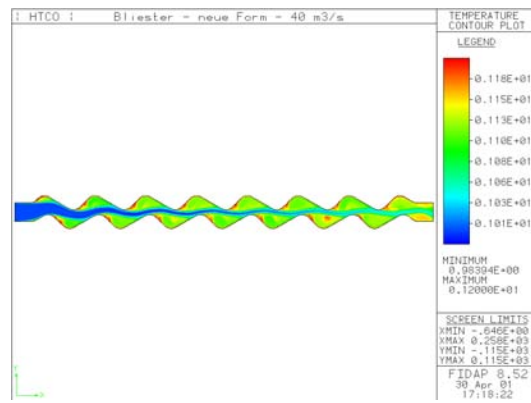


Fig. 8 Velocity (Detail)

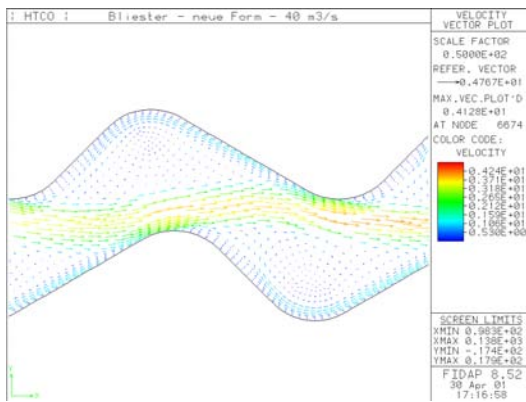


Fig.9 Temperature Distribution

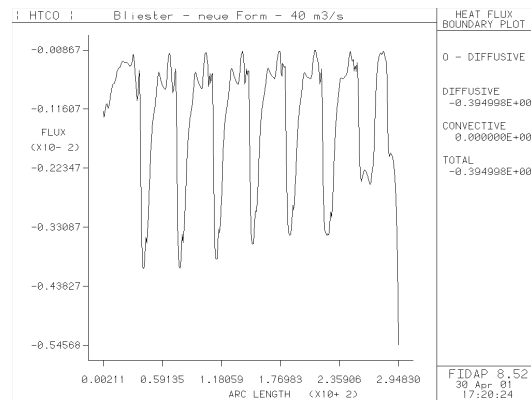


Fig. 10 Heat transfer (one surface)

The CFD simulation finally led to a computational heat transfer of  $Q = 275$  W. The initial experimental evaluation of this exchanger showed an actual heat transfer of  $Q = 300$  W.

According to these encouraging results this new type of heat exchanger has been meanwhile patented (Joma-Polytec GmbH, Germany), built and is running in a pre-series of the next generation of household devices.

Heat exchangers made from plastic: not just a vision but a reality.

[1]: VDI – Wärmeatlas, 5. edition, VDI-Verlag, Düsseldorf, Germany