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ABSTRACT

The bulb of a thermostatic expansion valve (TXV) is basically a temperature-pressure converter. It senses the temperature at the outlet of the evaporator, and the substance in the bulb (charge) generates the corresponding saturation pressure inside the bulb. The bulb is mounted on the evaporator outlet with a special mounting strap. The heat transfer is quite complex because it takes place both directly through the contact points between bulb and pipe and indirectly through the mounting strap
The TXV has to react to temperature changes at the evaporator outlet. Therefore, the dynamic behavior of the valve (and thereby the whole refrigeration system) depends greatly on the heat transfer between the evaporator outlet tube and the charge in the bulb.

In this paper a model for the overall heat transfer between the pipe and the charge is presented. Geometrical data and material properties have been kept as parameters in order to be able to see the effect of changes in those. Some of the parameters (e.g. thermal contact resistances) have been determined by a finite element model and a series of experiments.
The model has been validated using test results obtained under different operating conditions and has been found to predict the time constant for the temperature development in the bulb within 1-10 %. Furthermore it has been found that app. 20% of the heat transfer takes place trough the mounting strap.

The work is part of the development of a complete model for different types of charges for TXV's.

1 INTRODUCTION

Thermostatic expansion valves (TXV) have been used as regulation devices in refrigeration systems for many years. The main purpose of the TXV is to meter the flow of refrigerant into the evaporator in order to maintain a certain superheat at the evaporator outlet. Furthermore the TXV divides the high pressure side from the low pressure side of the refrigeration plant.
The bulb of the TXV is mounted at the outlet of the evaporator where it senses the temperature. In the static situation, the temperature of the bulb will stabilize somewhere between the ambient temperature and the temperature of the evaporator outlet tube. In the dynamic situation however, it is important to know the dynamics of the temperature response.
In the literature known to the author, there have only been a few investigations on the dynamic temperature response of the charge for a TXV. The work closest related was published by James & James (1987). They developed a mathematical model for a TXV. Part of that model describes the dynamics of the charge. Unfortunately they did not quantify the thermal resistance between the bulb wall and the evaporator tube. Also they did not take the strap with which the bulb is mounted into account.
During the work presented in this paper a mathematical model for the temperature response of the charge was developed. The model is a lumped mass model which includes the heat transfer of the mounting strap. The mathematical model has been validated through experimental tests under various conditions.

2 THE MATHEMATICAL MODEL

The bulb is mounted on the evaporator tube as shown in Figure 1.

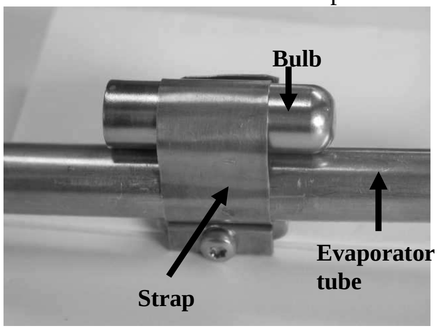


Figure 1: Bulb mounted on evaporator tube

Changing the surface temperature of the evaporator outlet, will cause the temperature of the charge to change. Over time the temperature of the charge will stabilize at a temperature between that of the evaporator outlet and the ambient temperature. In the present work, this response is treated as a first order system.
The response of a first order system to a unit step change is described by Equation 1.

$$y(t) = 1 - e^{\frac{-t}{\tau}}$$

Where:

y	:Response
t	:time
ι	:Time constant

Equation 1 (Raven (1996))

The model needed is a model that describes the temperature development in the charge as a reaction of a change of the surface temperature of the evaporator outlet tube. In order to describe the heat flow in the construction some definitions have to be presented. The construction can be divided into 8 parts as shown in Figure 2.

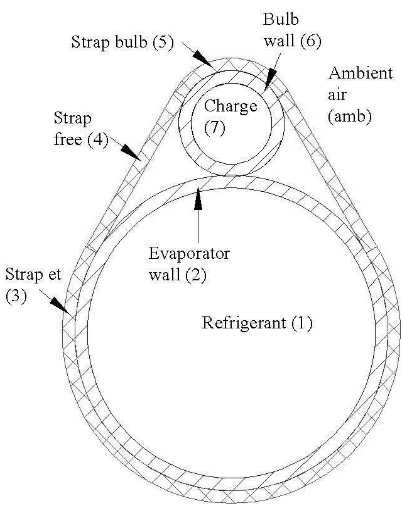


Figure 2: Definition of thermal system

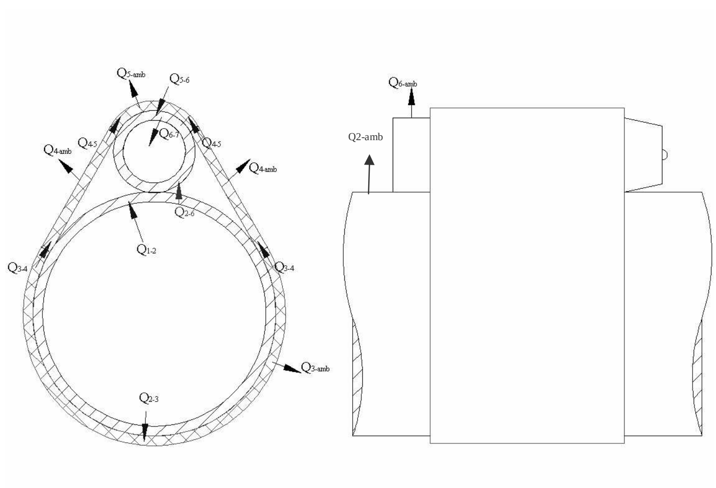


Figure 3: Heat fluxes in the system

The heat flows in the system are shown in Figure 3. In a more schematic way, the heat fluxes can be illustrated as shown in Figure 4.

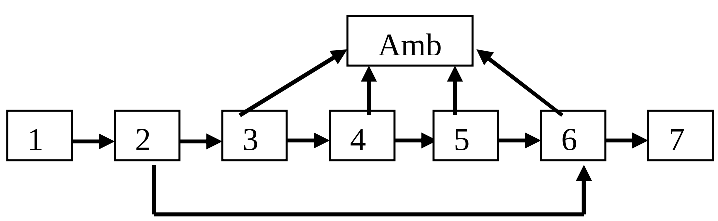


Figure 4: Heat fluxes in the system

From Figure 4 it can be seen that the temperature of the charge is a result of two different series of heat fluxes in the system. They are:

1. Refrigerant (1) ⇒ Evaporator tube wall (2) ⇒ bulb wall (6) ⇒ Charge (7)
2. Refrigerant (1) ⇒ Evaporator tube wall (2) ⇒Strap et (3) ⇒Free strap (4) ⇒Strap bulb (5) ⇒ bulb wall (6) ⇒ Charge (7)

In order to simplify the modeling, the following assumptions are made:

- Lumped mass model
- No temperature profile through or along the perimeters of walls.
- Strap has no mass
- The strap is modeled as a fin where the temperatures at the endpoints are known.

Heat flux in the above system:

$$\dot{Q}_{1-2} = h_{ref} \cdot A_{et\_i} \cdot \Delta T_{1-2}$$ **Equation 2**

$$\dot{Q}_{2-6} = \frac{1}{R_{c_{2-6}}} \cdot \Delta T_{2-6}$$ **Equation 3**

$$\dot{Q}_{2-3} = \frac{1}{R_{c_{2-3}}} \cdot \Delta T_{2-6}$$ **Equation 4**

$$\dot{Q}_{2-amb} = h_{air} \cdot A_{et\_strap} \cdot \Delta T_{2-amb}$$ **Equation 5**

$$\dot{Q}_{3-4} = 2 \cdot M \cdot \frac{\cosh(m \cdot L_{strap\_free}) - \frac{\theta_l}{\theta_b}}{\sinh(m \cdot L_{strap\_free})}$$ **Equation 6**

$$\dot{Q}_{4-5} = 2 \cdot M \cdot \frac{\frac{\theta_l}{\theta_b}\cosh(m \cdot L_{strap\_free}) - 1}{\sinh(m \cdot L_{strap\_free})}$$ **Equation 7**

$$\dot{Q}_{5-6} = \frac{1}{R_{c_{5-6}}} \cdot \Delta T_{5-6}$$ **Equation 8**

$$\dot{Q}_{5-amb} = h_{air} \cdot A_{b\_strap} \cdot \Delta T_{5-amb}$$ **Equation 9**

$$\dot{Q}_{6-7} = h_{charge} \cdot A_{b\_i} \cdot \Delta T_{6-7}$$ **Equation 10**

$$\dot{Q}_{6-amb} = h_{air} \cdot A_{b\_free\_amb} \cdot \Delta T_{6-amb}$$ **Equation 11**

$$\dot{Q}_{2-3} = \dot{Q}_{3-amb} + \dot{Q}_{3-4}$$ **Equation 12**

$$\dot{Q}_{4-5} = \dot{Q}_{5-amb} + \dot{Q}_{5-6}$$ **Equation 13**

$$\dot{Q}_{4-amb} = \dot{Q}_{3-4} - \dot{Q}_{4-5}$$ **Equation 14**

$$\theta_l = T_5 - T_{amb}$$ **Equation 15**

$$\theta_b = T_3 - T_{amb}$$ **Equation 16**

$$m^2 = \frac{h_{air} \cdot P_{strap}}{\lambda_{strap} \cdot A_{strap\_cross}}$$ **Equation 17**

$$M = \sqrt{h_{air} \cdot P_{strap} \cdot \lambda_{strap} \cdot A_{strap\_cross}} \cdot (T_2 - T_{amb})$$ **Equation 18**

Combining these heat fluxes to describe the three ways the bulb is affected, results in following equation system:

$$m_2 \cdot c_{p2} \frac{dT_2}{dt} = \dot{Q}_{1-2} - \dot{Q}_{2-3} - \dot{Q}_{2-6}$$ **Equation 19**

$$m_6 \cdot c_{p6} \frac{dT_6}{dt} = \dot{Q}_{2-6} + \dot{Q}_{5-6} - \dot{Q}_{6-7} - \dot{Q}_{6-amb}$$ **Equation 20**

$$m_7 \cdot c_{p7} \frac{dT_7}{dt} = \dot{Q}_{6-7}$$ **Equation 21**

3 THERMAL RESISTANCES

The model presented above includes three thermal resistances $R_{c\ 2\text{-}6}$, $R_{c\ 2\text{-}3}$ and $R_{c\ 5\text{-}6}$. These have been determined by the help of experimental tests and a finite element model. In the following these tests and the finite element model will be presented. The resulting thermal resistances will be inserted into the analytical model which then again will be compared to test results.

3.1 Experimental evaluation of the temperature distribution in empty bulb

In the simulations, the contact resistances will be the unknown values to determine. Therefore the temperature distribution in the bulb wall needs to be known.
This has been done experimentally by measuring the temperature at four points inside an empty bulb. The temperature was measured at four points as shown in Figure 5.
The measured temperature curves have been used to calibrate the FE model.

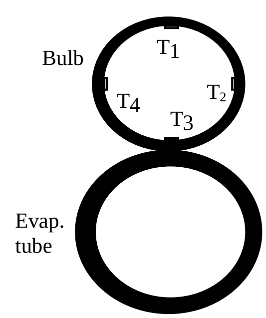


Figure 5: Temperature sensors

3.2 Test series

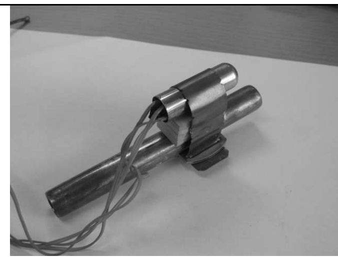
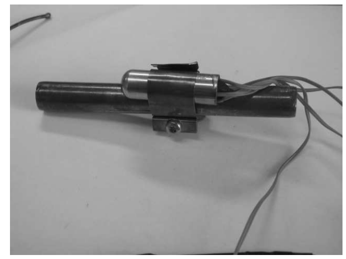
The test series covers tests of the two contacts individually and a combination.
Three tests were performed with conditions as shown in Table 1.

	Pipe contact (Contact 1)	Strap contact (Contact 2)
Test 1	X	
Test 2		X
Test 3	X	X

Table 1: Tests performed on bulb with temperature sensors

The tests show the temperature distribution in the bulb.

3.3 Results

Test 1		Test 2		Test 3	
 Figure 6: Wooden brick as insulation between strap and bulb		 Figure 7: Wooden brick as insulation between pipe and bulb		 Figure 8: Full contact	
Sensor	**Time constant**	**Sensor**	**Time constant**	**Sensor**	**Time constant**
1	144	**1**	48	**1**	70
2	120	**2**	57	**2**	43
3	10	**3**	149	**3**	9
4	122	**4**	57	**4**	63

3.4 The Finite element model

The finite element (FEM) software used for this investigation is SORPAS®.
For simplicity the problem is modeled as a 2- dimensional problem. Figure 9 and Figure 10 show the real system and the modeled section respectively.

The FE model looks slightly different from the real model. The differences are partly caused by modeling limitations and partly due to numerical issues.

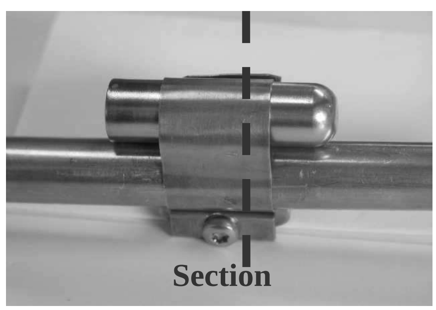


Figure 9: Real system

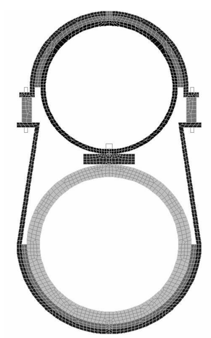


Figure 10: Modelled section

3.5 Boundary conditions

For a SORPAS® model it is required to model tools where the mechanical boundary conditions can be applied. The mechanical boundary condition for this model is an initial movement of the bulb towards the pipe. In the Danfoss refrigeration laboratory it has become common practice to tighten the strap until the bulb has moved 1 mm into the pipe, which results in a deformation of the copper tube. This is also done in the simulations.
The thermal boundary condition is that the copper tube keeps its temperature constant during the simulation. It has been chosen to set the temperature of the copper tube to 0ºC while all other parts have an initial temperature of 5ºC. Ambient temperature is set to 5ºC but the model is considered as being insulated from the ambient.

3.6 Calculations

The contact between two parts will never be as perfect in reality as it can be modeled theoretically. In order to compensate for this difference, interface layers are used. The interface layer is a material with a given conductivity and with very low heat capacity which is put in between the real contact faces. The thickness and conductivity of the interface layer will determine the heat flow between the two parts.

Basically this model needs two different interface layers, one between the bulb and the pipe (contact 1) and one between the strap and the bulb (contact 2). The thickness of both has been set to 0.5 mm. Following procedure was used to find the conductivity of them

Initially a number of calculations for different conductivities of the interface layers were performed. The conductivity of one interface is varied while the other is set to 0.001 W/m/k. These analyses are comparable with the experimental results where one contact is insulated while the other is not.

3.7 Results

For the contact 1, it was found that a conductivity of 0.75 W/m/K for the interface layer gave the results closest to the experimental results. Whereas for the contact 2 it was found that a conductivity of 0.075 W/m/K gave the closest results.

Table 2 shows the results obtained.

	Measured	**FEM**	**Deviation**	**Deviation in %**
Contact 1				
Sensor 1	144	167	23	16
Sensor 2	120	117	-3	-2.5
Sensor 3	10	10	0	0
Contact 2				
Sensor 1	48	45	-3	-6
Sensor 2	57	65	8	14
Sensor 3	149	110	-39	-26

Table 2: Comparison of time constants [s] for increasing temperature

3.8 Thermal resistance

The thermal resistance R is defined as:

$$R = \frac{l}{\lambda \cdot A} \cdot t$$

Equation 22
(Incorpera and DeWitt (1996))

Thus the thermal resistances R can be found:

Contact	**Area [m^2]**	**λ [W/m/K]**	**t [m]**	**R [K/W]**
Bulb/pipe	7.40E-5	0.75	0.0005	**9**
Strap/bulb	4.787E-4	0.075	0.0005	**13.9**
Strap/evaporator tube	5.721E-4	0.075	0.0005	**11.6**

Table 3: Thermal resistances

3.9 Conclusion on the finite element simulations

The finite element calculations have given an estimate of the thermal resistances of the two contacts. These can now be used in the analytical lumped mass model. For further verification the results from the analytical model have been compared to experiments with charged bulbs where the pressure of the bulb was measured.

4 THE ANALYTICAL MODEL

The contact resistances can be inserted in a previous modeled lumped mass model of the charged system presented in section 2.

Inserting the given conditions, the model should be able to predict the time constants as measured on the charged bulbs. In order to see the effect of each of the two contacts, three comparisons are made. One for only pipe contact (insulated strap), one for only strap contact (insulated pipe), and one in which both contacts are active. Furthermore one comparison is made for a larger amount of charge also with both contacts active.

4.1 Test on charged bulbs

Some tests were performed on bulbs charged with a very small amount of charge (80 mg Propane (R290)).
The bulbs were mounted in four different ways. Some were mounted on the top of the pipe, where the liquid charge will be close to the pipe and some underneath the pipe, where the liquid charge will be close to the strap.

	Mounted on top	Mounted underneath	Strap insulated	Pipe insulated
Bulb 1	X			X
Bulb 2	X		X	
Bulb 3		X	X	
Bulb 4		X		X

Table 4: Mounting of the four bulbs

Results:

	Time constant up	Time constant down
Bulb 1	245	122
Bulb 2	75	15
Bulb 3	219	103
Bulb 4	127	33

Table 5: Time constants for the four bulbs

The right comparison for the time constant going upwards can be made between bulb 2 for Contact 1 and bulb 3 for contact 2. For the time constant going downwards on the other hand, the right comparison can be made between bulb 1 for insulated pipe and bulb 4 for insulated strap.

	Strap insulated	Pipe insulated	Scale
Time constant up	75	219	1:2.92
Time constant down	33	122	1:3.7

Table 6: Comparable time constants for the two contact interfaces

4.2 Results

	Test	Model	Deviation in %
R290 80 mg, strap contact (insulated pipe)	219	232	6
R290 80 mg, only pipe contact (insulated strap)	75	77.9	4
R290 80 mg (both contacts)	52	58.5	12.5
R290 1630 mg (both contacts)	62	62.5	0.8

Table 7: Comparison of time constants from tests and calculations

5 CONCLUSION AND FURTHER WORK

Using the thermal resistances found by Test/ FEM, the model predicts the time constants for the two systems with an accuracy of 1-13 %. Furthermore, the measured time constants show that the direct contact between bulb and evaporator pipe transfers 75-80% of the heat, while the strap transfers the remaining 20-25%.

This work is part of a project with the aim to develop a model for the static and dynamic behavior of charges for TXV. Therefore, this work needs to be extended to include charges with thermal ballast brick and/ or non-condensable gas.

NOMENCLATURE

h_{ref}	: Heat transfer coefficient of refrigerant	$[W/m^2/K]$
h_{charge}	: Heat transfer coefficient of charge	$[W/m^2/K]$
R_{c_2-6}	: Contact resistance between etube/bulb	$[m^2\ K / W]$
R_{c_2-3}	: Contact resistance between etube/strap	$[m^2\ K / W]$
R_{c_5-6}	: Contact resistance between strap/bulb	$[m^2\ K / W]$
P_{strap}	: Perimeter of strap	[m]
h_{air}	: Heat transfer coefficient of air	$[W/m^2/K]$
λ_{strap}	: Heat conductivity of strap	[W/K/m]
A_{et_strap}	: Contact area between strap and evap tube	$[m^2]$
A_{b_strap}	: Contact area between strap and bulb	$[m^2]$
$A_{b\_free\_amb}$	: Part of bulb surface that is free to ambient	$[m^2]$
A_{et_i}	: Inner area of evaporator tube	$[m^2]$
A_{b_i}	: Inner area of bulb	$[m^2]$
A_{strap_cross}	: Cross sectional area of strap	$[m^2]$
L_{strap_free}	: Length of free strap	[m]

REFERENCES

1. Incropera, F. P., De Witt, D. P., 1996, *Introduction to heat transfer*, John Wiley and sons, Inc., USA, 801 pages.
2. James, K.A., James R.W., 1987, Transient analysis of thermostatic expansion valves for refrigeration system evaporators using mathematical models, *Trans. Inst. M C Vol. 9 No. 4.*
3. Raven H. F., 1995, *Automatic Control Engineering*, McGraw Hill, Singapore, 619 pages.