DECREASING COOL-DOWN TIME OF A JOULE-THOMSON MICROCOOLER

by introducing multiple closable restriction channels

UNIVERSITEIT TWENTE.

EMS

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1 Introduction

As long as there are devices that produce heat, coolers are needed to make sure the temperature does not get too high. For the device might not work at a high temperature or might even break down. It is possible to cool down an entire room, with air conditioners for example, in order to keep the device at the desired temperature. But this costs a lot of energy and a lot of other devices. A fan can be placed on the device itself, like the fans found on laptops. This is a lot more efficient, but for some devices this will not be enough. For these devices very small coolers have been invented. One of these inventions is the Joule-Thomson microcooler.

This microcooler is made for devices which operate at a low temperature close to 100 Kelvin and uses the Joule-Thomson effect. This effect happens when a high-pressure gas is depressurized. Under certain conditions the gas will cool down. The microcooler is designed in such a way that a continuous high-pressure gas flow is depressurized very sudden. This is done by leading the gas through a rectangular channel; at the end of the channel a restriction is placed, making the pathway for the gas suddenly very narrow. At the other side of the restriction the pressure will be much lower and the temperature drop will be considerate. The low-pressure gas, now with a very low temperature, can absorb the heat of the device to which the cooler is attached to and carries this heat away from the system.

Once the operating temperature of the microcooler is reached, the system works perfectly and a lot of generated heat will be dealt with. The emphasis in the previous sentence lies on 'once the operating temperature is reached', because it takes a long time for the microcooler to reach this temperature. This study will be on how the microcooler can cool down faster. This is dependent on a lot of factors, but this study will be limited to manipulating the restriction.

Therefore, the research question of this study is: how can the restriction of a Joule-Thomson microcooler be manipulated to decrease the cool-down time of this cooler, without effecting the working of the cooler once it has cooled down?

This study is a bachelor assignment for the bachelor Advanced Technology at the University of Twente. In order to find ways to manipulate the restriction properly, the microcooler should first be understood properly and some results should be obtained to which the new possibilities can be compared. There will be several other constraints to the new possibilities and some findings will be better than others. The chapters of this study will follow in this order.

The assignment is purely theoretical and no laboratory tests or any other kind of physical testing was done to verify the results of this study. The results of this study should be verified by experiments and if this verification is successful, they can be implemented into new Joule-Thomson microcooler designs.

2 List of symbols

In this study a number of symbols are used. Here follows an overview of the symbols, their meanings and their units.

c	specific heat	[J/(kg·K)]
h	height	[m]
h_t	heat transfer coefficient	[W/(m²·K)]
l	length	[m]
$\dot{m}$	mass-flow rate	[kg/s]
t	time	[s]
w	width	[m]
x	distance	[m]
A	area	[m²]
C	heat capacity	[J/K]
D_h	hydraulic diameter	[m]
H	enthalpy	[J]
Nu	Nusselt number	[-]
P	pressure	[Pa]
$\dot{Q}$	heat flow rate	[J/s] or [W]
T	temperature	[K]
α	thermal expansion coefficient	[µm/(m·K)]
ε	emissivity	[-]
λ	thermal conductivity	[W/(m·K)]
μ	viscosity	[Pa·s]
μ_{JT}	Joule-Thomson coefficient	[K/Pa]
ρ	density	[kg/m³]
σ_b	Stefan-Boltzmann constant	[W/(m²·K⁴)]

3 Theory behind the Joule-Thomson Microcooler

The Joule-Thomson microcooler has its name because:

a. it is made to cool down devices
b. it has parts that are several micrometers in size
c. it cools down by using the Joule-Thomson effect

This Joule-Thomson effect will be explained in this chapter, after which the current design will be presented and the thermodynamics of the system will be discussed.

3.1 Joule-Thomson Effect

When a high-pressure ideal gas (a gas that has no interaction between its molecules and all molecules are considered to have no physical size) is led through a small opening to a place where the pressure is lower, the temperature of the gas will stay the same. When however, the molecules of a gas interact with one another the temperature will change. This change can be positive as well as negative.

There are two mechanisms which influence this change in temperature. Firstly, when the gas expands the average distance between the molecules is increased, thus increasing the potential energy. This increase in potential energy causes a decrease in kinetic energy and consequently a decrease in temperature. Secondly, the number of collisions between the gas molecules is decreased. This causes, on average, an increase in kinetic energy and thus an increase in temperature. The combination of these two mechanisms is called the Joule-Thomson effect. The effect is commonly denoted by the Joule-Thomson coefficient which is defined as [[1], *chapter 1.2*]:

$$\mu_{JT} = \left(\frac{\partial T}{\partial P}\right)_H$$

Here, ∂T is the change in temperature and ∂P is the change in pressure. This happens under constant enthalpy (H). The enthalpy will remain constant when no heat is exchanged with the environment.

Since the effect only deals with decreasing pressure, ∂P is always negative, which means that when a fluid has a positive μ_{JT}, ∂T will be negative and vice versa.

The Joule-Thomson effect is highly dependable on temperature and varies for different substances. At relatively high temperatures the effect due to the decrease in the number of collisions dominates and the gas will heat up when expanded. When the temperature drops below a certain inversion temperature, the increase in distance between the molecules will dominate and the gas will cool down upon expansion. In this study only gasses will be discussed that have a positive Joule-Thomson coefficient under the used conditions.

3.2 Current Cooler Design

Now the current microcooler will be discussed. In figure 1, a schematic cross-section the current cooler is shown.

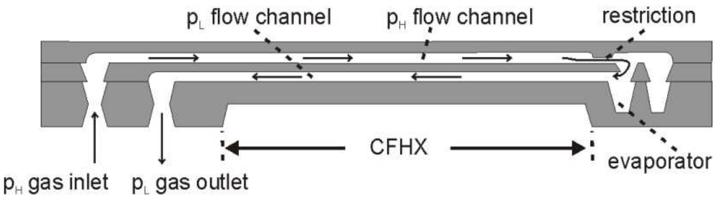


Figure 1: schematic of the current microcooler

As you can see in figure 1, the cooler has a high-pressure gas inlet and a low-pressure gas outlet. The gas is first led through a counter-flow heat-exchanger (CFHX). The cooler low-pressure gas cools the high-pressure gas, so the CFHX pre-cools the gas before it expands. Next to the obvious result of cooler gas, this will also increase the Joule-Thomson coefficient. At the end of the CFHX the gas is met by a restriction. The restriction will cause the necessary pressure drop, because it is the narrowest part the gas has to flow through. The restriction is also the decisive factor of the design for the mass-flow through the system and this study will focus mainly on manipulating this restriction to obtain the desired decrease in cool-down time. The part of the cooler behind the restriction is called the cold tip and this can be physically connected to any device which needs cooling. When the boiling point of the fluid is reached, some liquid will be created and the fluid will be in two-phase. The liquid which is created is held in the evaporator and the amount of liquid contributes to the amount of cooling power which is still unused. The fluid leaves the cold tip through the low-pressure channel of the CFHX and leaves the cooler after that. This gas can be disposed of or repressurized and sent back into the cooler depending on the system that is used.

This cooler is made entirely from glass. This was found to be a good material to both somewhat insulate the cold tip from the inlet/outlet, but still leaving enough conduction through the middle wafer of the CFHX.

In order to maintain the structural strength, pillars are placed within the channels. The pillar density depends on the forces within the channels, thus the density is higher in the high-pressure channel. The dimensions of CFHX and other aspects of the cooler have been optimized. One of these aspects is the thermal emissivity, which is reduced by coating the cooler with a thin layer of gold. A lot of fluids can be used for the microcoolers, but the fluid used in this study is nitrogen. In table 1 several design aspects can be found, these are taken from Lerou et al. (2007, [2]).

Dimensions of the cooler	**[m]**	**Pillars in the channels**	
Width of the cooler	$2{,}20 \cdot 10^{-3}$	Pillar density high-P channel	$22{,}5 \cdot 10^{6}$ m^{-2}
Width of the channels	$2{,}00 \cdot 10^{-3}$	Pillar diameter high-P channel	$200 \cdot 10^{-6}$ m
Height of the channels	$50{,}0 \cdot 10^{-6}$	Pillar density low-P channel	$2{,}75 \cdot 10^{6}$ m^{-2}
Length of the CFHX	$25{,}0 \cdot 10^{-3}$	Pillar diameter low-P channel	$50 \cdot 10^{-6}$ m
Height of the restriction (gap)	$305 \cdot 10^{-9}$		
Length of the restriction	$140 \cdot 10^{-6}$	**Materials used**	
Thickness of the top wafer	$125 \cdot 10^{-6}$	Material of the cooler	Glass
Thickness of the middle wafer	$95{,}0 \cdot 10^{-6}$	Coating of the cooler	Gold
Thickness of the bottom wafer	$150 \cdot 10^{-6}$	Working fluid	Nitrogen

Table 1: design aspects of the current design

3.3 Enthalpy Flow and Heat Flows

In order to design a good microcooler, the flows of heat and enthalpy of the system should be understood properly. Derking (2011) [[3], *chapter 3.1*] wrote more about this.

Because the fluid flows through the channels and the temperature can be different at each place in the system, the fluid undergoes a change in enthalpy. Since the pressure is assumed constant in the high-pressure channel and constant in the low-pressure channel, the change of enthalpy ($d\dot{H}$) in a small section of the channels is given by:

$$\frac{d\dot{H}}{dx} = \dot{m} \cdot c_p \cdot \frac{dT}{dx}$$

Here, x is the place along the length of the channel, $\dot{m}$ is the rate of mass flow, c_p is the local specific heat of the fluid and dT is the local temperature difference.

Next there are the conductive and convective heat flows in the system. There is conductive heat flow along the length of each of the three wafers through the glass and through the gold layer. Also, the pillars within the channels will conduct heat between the wafers and there will be conduction from the high-pressure channel to the low-pressure channel through the middle wafer. Between the fluid and the walls and pillars of the channel both conductive and convective heat flow will take place. The ratio between the convective and conductive heat flow between a fluid and its channel can be given by the Nusselt number (Nu) and is defined as:

$$Nu = \frac{h_t \cdot D_h}{\lambda_f}$$

Here, h_t is the local heat transfer coefficient, λ_f is the thermal conductivity of the fluid and D_h is the hydraulic diameter which can be written as:

$$D_h = \frac{4 \cdot A_c}{O}$$

With, A_c being the cross-sectional area and O the perimeter of the channel. When the flow is fully developed laminar, the Nusselt number is constant and determined by the shape of the channel. Because of the pillars the number deviates for the number of a rectangular channel. Since the pillar structure is different for the high-pressure and the low-pressure channel, different Nusselt numbers are found. After some approximations explained by Derking (2007, [[3], *chapter 3.1*]) the Nusselt number of the high-pressure channel is 4,65 and for the low-pressure channel it is 6,45.

We can now rewrite the formula as: $h_t = Nu \cdot \lambda_f / D_h$ and use this heat transfer coefficient for the convective heat flow ($\dot{Q}_{conv}$) between the fluid and the channel walls:

$$\dot{Q}_{conv} = -h_t \cdot A_{hx} * \Delta T$$

A_{hx} is the area of heat exchange and ΔT is the temperature difference between the fluid and the wall.

The conductive heat flow ($\dot{Q}_{cond}$) is given by:

$$\dot{Q}_{cond} = -\lambda_m \cdot A_c \cdot \frac{dT}{dx}$$

Here, λ_m is the thermal conductivity of the wafer material, A_c is the cross-sectional area of the wafer and dT is again the local temperature difference.

Lastly there will be radiative heat flow, the reason for the gold coating of the microcooler. Heat radiation takes place through electromagnetic waves and happens even in a vacuum. The radiation ($\dot{Q}_{rad}$) between an object completely enclosed by a second object is given by:

$$\dot{Q}_{rad} = \frac{\sigma_b \cdot A_1 \cdot ({T_2}^4 - {T_1}^4)}{\frac{1}{\varepsilon_1} + \frac{A_1}{A_2} \cdot (\frac{1}{\varepsilon_2} - 1)}$$

With, σ_b being the Stefan-Boltzmann constant, ε the emissivity, A the surface of radiation and T the temperature of the object. With the microcooler the area surrounding the microcooler is much bigger than the outer area of the microcooler and the formula is simplified to:

$$\dot{Q}_{rad} = \varepsilon_c \cdot \sigma_b \cdot A_{rad} \cdot ({T_{env}}^4 - {T_c}^4)$$

With the subscript c standing for the microcooler. The emissivity of glass is around 0,8 – 0,95. The emissivity of gold is 0,02 and with temperature differences of about 200 Kelvin between the microcooler and the environment, this minimizes the radiative heat flow into the system.

3.4 Mass-flow

Due to the conservation of mass the rate of mass-flow is the same everywhere in the system. The mass flow is determined by the place in the system where the flow has the most resistance and that is at the restriction. If the Joule-Thomson expansion is adiabatic and isenthalpic, the mass-flow through a rectangular channel can be calculated by [[3], *chapter 3.2*]:

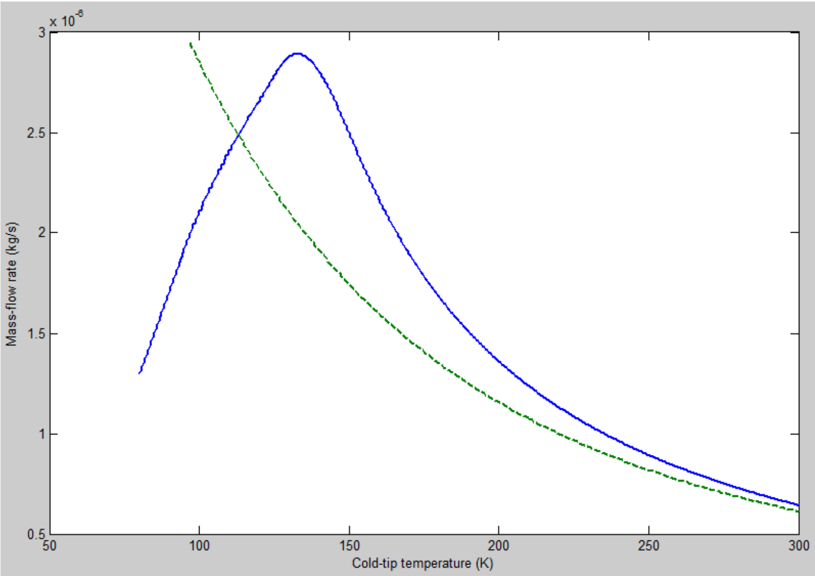
$$\dot{m}(H) = \frac{w \cdot h^3}{12 \cdot l} \cdot \int_{P_l}^{P_h} \frac{\rho(H,P)}{\mu(H,P)}\, dP$$

Here, w, h and l are the width, height and length of the restriction and P_h and P_l are the high pressure and the low pressure.

When the temperature of the gas flowing in the restriction and the evaporator is considered equal (this can be done because the restriction is in close contact with the evaporator), the Joule-Thomson expansion becomes isothermal and the mass-flow rate can be calculated by:

$$\dot{m}(T) = \frac{w \cdot h^3}{12 \cdot l} \cdot \int_{P_l}^{P_h} \frac{\rho(T,P)}{\mu(T,P)}\, dP$$

When we input the dimensions of the restriction and use data on the density and the viscosity from REFPROP by NIST [4], the mass-flow can be found as a function of temperature by numerical integrating between the high and low pressures of 80 bar and 6 bar. For comparison the enthalpies are translated into temperatures by using the same databases. The results are shown in graph 1. The green dashed line is the mass-flow rate from isenthalpic expansion and the blue solid line is the mass-flow rate from isothermal expansion. In reality the mass-flow rate follows the isenthalpic expansion rate to some extend during the first time of cooling down. Below a certain temperature the mass-flow rate will follow the isothermal rate.



Graph 1: mass-flow rate of the current microcooler

At the start of the cool-down, the mass-flow is still quite low. As the fluid cools down, the mass-flow increases automatically. Another factor which is not displayed here is the heat capacity of the fluid; this is strongly dependent on temperature and quite high at the start of the cool-down. This high heat capacity has the effect that the heat which is transferred from the high-pressure channel to the low-pressure channel does not have a big influence on cooling the fluid.

4 Modelling the Cooler

4.1 Designing the model

The problem with the current microcooler which is addressed in this study is the long cool-down time. In order to test the possible solution to this problem a model is made in MATLAB Simulink [5]. For the model the counter-flow heat-exchanger (CFHX) is divided into several segments of equal length and the cold tip together with the restriction and evaporator is taken as one segment. The CFHX is further divided into a top wafer, a middle wafer, a bottom wafer, a high pressure channel and a low pressure channel. The Joule-Thomson expansion is modelled isenthalpic: high pressure, high temperature fluid flows out of the last high pressure channel-segment and low pressure, low temperature fluid flows into the cold tip. The mass flow is equal in the entire system. All emissive, convective and conductive heat flows are taken into account, including flow through the pillars. The pillars are divided in half and added to their nearest wafer. The temperature of the environment is set steady at 300 K, this includes the inlet/outlet part of the wafer.

The data for the properties of the fluid (nitrogen) is taken from REFPROP by NIST [4] and are dependent on temperature and pressure. The properties of the solids (glass) are considered to be constant.

On the next page the structure of the model is displayed in figure 4. All arrows (except those connected to the scopes) represent a flow of energy; they are conductive heat, convective heat or enthalpy. Within each 'wafer' block and in the 'Evaporator' a separate radiative heat flow is added. Segments 0 (which is always at environment temperature), segments 1 and segments 2 are displayed. After those there can be a number of CFHX segments until segment N, which is displayed again. This last segment is connected to the cold tip (here it is labelled 'Evaporator'). The block labelled 'Massflow' has an input of the temperature of the 'Evaporator' and an output to every other block in the system. As an example the contents of 'Massflow' (figure 2) and the 'Evaporator' (figure 3) are shown below. The conductive heat flows into 'Evaporator' are denoted with Qc. They are added to the enthalpy flow off the fluid from the high-pressure channel after the fluid has passed the restriction ('JT expansion'). The minus sign in the 'Add' block is for the enthalpy flow out of the 'Evaporator' into the low-pressure channel. The temperature of the 'Evaporator' is used for calculating this enthalpy flow and also for the radiative heat flow and the heat capacity. Since $H = C \cdot T$ and $\frac{dH}{dt} = \sum \dot{Q} + \Delta\dot{H}$, (with C being the heat capacity and t being the time), this gives the equation being solved in this model block: $T = \int_{time} \frac{\sum \dot{Q} + \Delta\dot{H}}{C}\, dt$

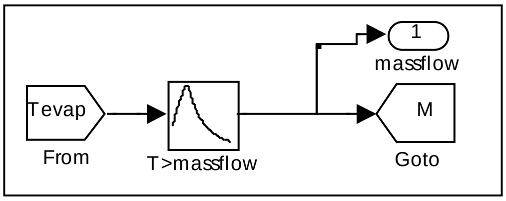


Figure 3: inside 'Massflow'

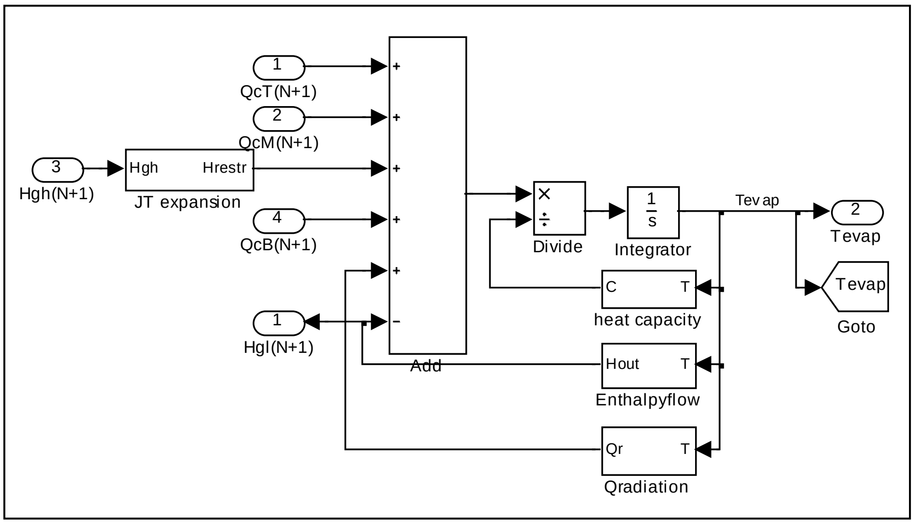


Figure 2: inside ' Evaporator'

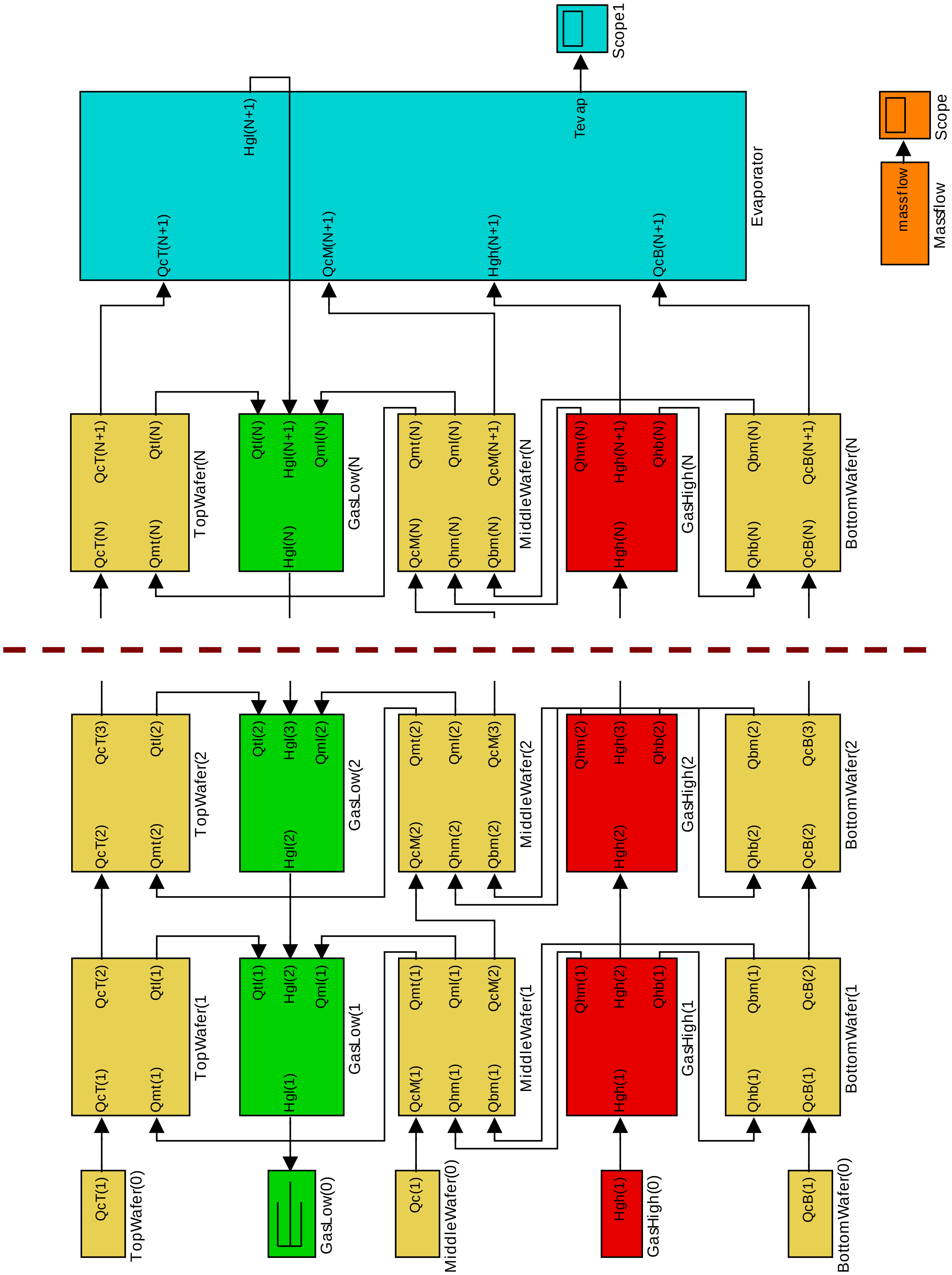
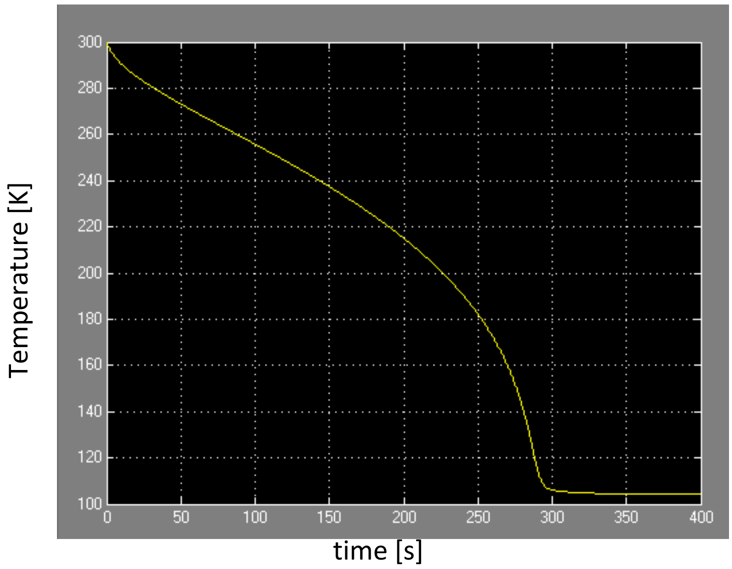


Figure 4: model of the Joule-Thomson microcooler

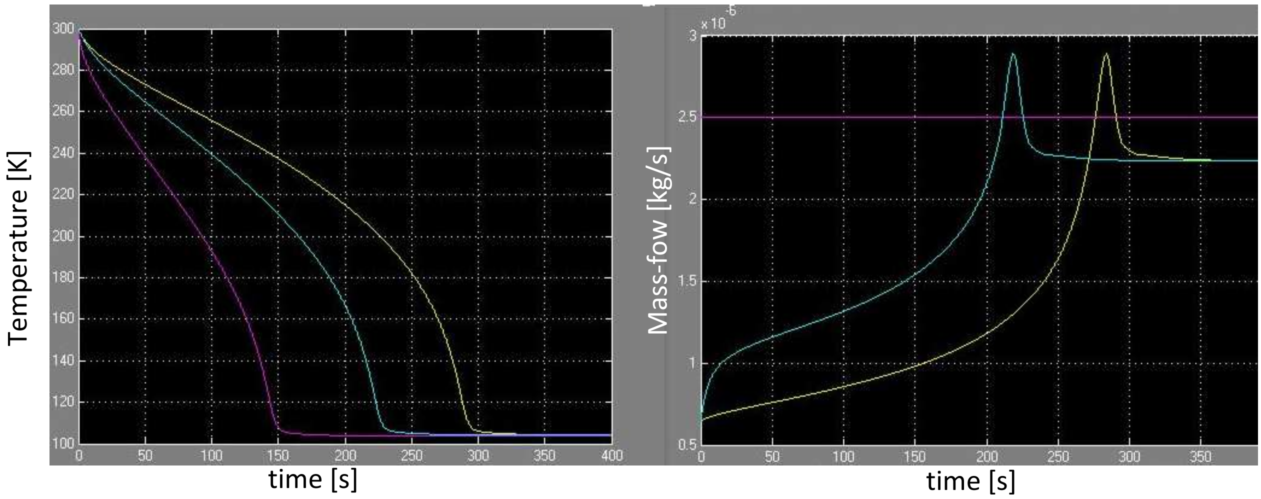
4.2 Preliminary results

The number of CFHX segments used for this model is ten. And the high and low pressures are still 80 bar and 6 bar respectively. At the beginning of the simulation all blocks have a temperature of 300 K. The results of running this model can be seen in graph 2. On the vertical axis the temperature in Kelvin is shown and on the horizontal axis the time that has passed in seconds. These results will be the benchmark for further results. When further on in this paper a model is mentioned and these kinds of results are shown, it will be based upon this model and axes will have the same units.



Graph 2: cool-down of the current microcooler

In order to get some feeling to what kind of mass-flows are required to cool down the system much faster, the model was also run with a constant mass-flow of 2,5 mg/s and with a mass-flow that was controlled by active feedback (the increase/decrease of some extra mass-flow atop of the normal mass-flow was controlled by the second derivative of the temperature). The results in graph 3 were obtained: to the right the corresponding mass-flows are shown, with on the vertical axis the mass-flow in kilograms per second.



Graph 3: cool-down and corresponding mass-flows of the current cooler and two fictional coolers

From these results the premature conclusion is drawn that more mass-flow results in faster cool-down times. Although the CFHX might not work as efficient with too high a mass-flow, because it will not be able to cool down the fluid well enough before it reaches the restriction.

5 Constraints of the New Design

The easiest way to increase the mass-flow would be to increase the size of the cooler all together. But there are some problems with that. The first being that the cool-down time might not actually decrease, because there is more material that has to be cooled down. Next to that, the whole idea of a microcooler is that it is small, with a lot of components in the range of micrometers. So there will be a constraint on the dimensions of the new design. Like this constraint, there will be other constraints and they will be listed here. Next to the constraints, there will be some aspects which are favourable and they can be used to choose between different valid designs.

So the first constraint will be that the size of the CHFX and of the cold tip must stay the same as in the original design.

The second constraint is that the net cooling power of the microcooler must still be sufficient. To make this concrete: at operating temperature the new aspects of the design may not cause more than 5 mW of heat entering the system. This includes the heat generated by the new aspects and extra heat flows from the environment into the system.

Thirdly, the design must be able to withstand the high pressures and low temperatures of the microcooler.

And the forth constraint is that the design must be able to be used over and over again. Once the microcooler is turned off, the entire systems warms up again to environment temperature and when the microcooler is turned on again it must behave in the same way as it did the first time. This means that all processes must be reversible.

Next to these constraints, the following aspects should be taken into account when choosing between different designs:

- Low heat dissipation or none at all
- Compatible with microelectromechenical systems
- Easy to integrate with the current design
- Few movable parts or none at all
- Materials can be bond to glass
- Low amounts of stress or none at all
- Few external connections or none at all
- Low heat capacity
- Low production costs
- Durability
- Leak tight

6 Possible Designs to Decrease Cool-down Time

An overview of the possible ways to decrease the cool-down time is shown in figure 5.

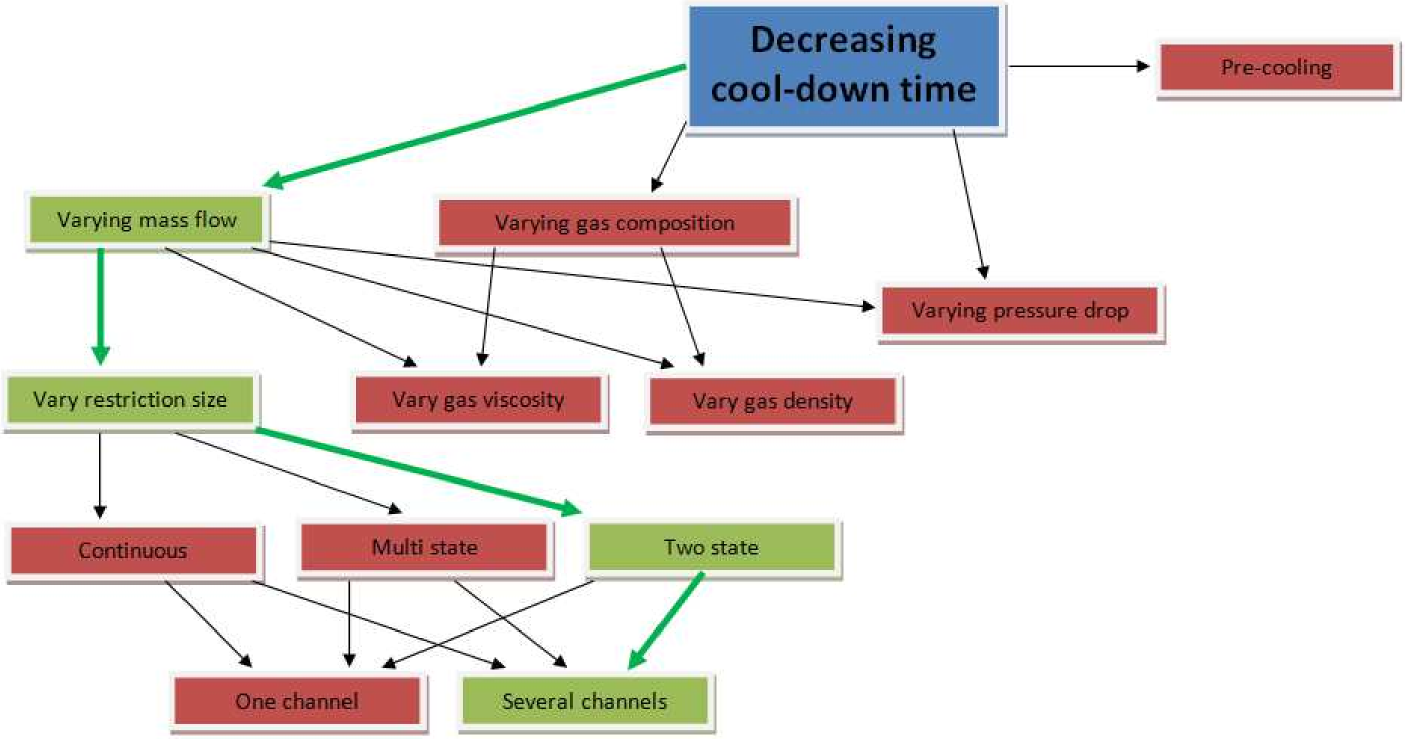


Figure 5: decision tree of ways to decrease cool-down time

The path with the thick green arrows shows the classification of the designs which were found to be the most promising and will be discussed in the most detail later on.
Since this study focuses on the possibilities relating to the restriction, the other possibilities will be discussed very briefly.

6.1 Ways to decrease cool-down time not related to the restriction

Pre-cooling: by pre-cooling either the working fluid or the micro-cooler itself from the outside, the system will start at a lower temperature and thus reach its desired temperature sooner. It is an easy solution but it will require extra equipment.
Varying pressure drop: by increasing the pressure drop during the start-up, both the mass flow and the Joule-Thomson effect are increased. Some design changes might be necessary in relation to the structural integrity, but this will not be further discussed in this study.
Varying gas composition: by changing the gas composition the properties of the working fluid can become more favourable. Two factors can be improved to increase the mass flow: the density can be increased or the viscosity can be decreased. Furthermore the heat of vaporization can be increased to allow more heat to be transferred from the cold tip to the fluid. To get the right gas mixture can be quite expensive or hard to obtain. The nitrogen in the current system is a simple and cheap option.
Varying mass flow: by increasing the mass flow, more fluid per second is cooled down by the Joule-Thomson effect. This means that more heat can be transferred out of the system. As described above, the mass flow can be varied by varying the pressure drop of changing the gas composition. This can be seen by looking at the factors determining the mass flow. The other factors that determine the mass flow are the dimensions of the restriction.

6.2 Varying the restriction size to change mass flow and reduce cool-down time

A lot of ways to manipulate the restriction were thought of and a lot of these ways were rejected on simple grounds such as physical impossibility or not meeting the design constraints discussed previously.

The first promising method was to use a different material than glass for the restriction. This material should be manipulated into expanding when it cools down or when it has reached a desired temperature. For clarification: the width of the channel would stay the same, the length of the restriction might change a bit and the height of the restriction would change the most. Since the mass-flow is dependent on the height to a power of three, this will be the decisive factor. During the start-up, the mass-flow should be very high, so the restriction will have a big gap. Now, when the material of the restriction expands, the gap will narrow and the mass-flow will decrease again towards its original value.

The next thing to consider is whether we want to switch between two states, switch between multiple states or making the states continuous. A state meaning a fixed physical size of the restriction. When the system would be actively controlled, energy would have to be added to the system and would most likely dissipate as heat. Since this would have a negative effect to the cool-down, the most logical thing to do is to create a system which is controlled by the temperature itself. Most materials contract when they cool down. But there are several options which create an opposite effect. The two that will be discussed here are hydrogels and materials with a negative thermal expansion coefficient.

Hydrogels are a kind of polymer that can hold a certain amount of water in between its molecules. There are different kinds of hydrogels with different actuators, but the focus here lies on those that have the temperature as their actuator. When the temperature goes down the polymer changes a bit and it can hold more water. If enough water is available the hydrogel will soak up the water and expands by doing so. The biggest problem with hydrogels is its temperature range. The microcooler cools down to about 100 Kelvin, but the water required by the hydrogel freezes at about 275 Kelvin. For this reason the hydrogels are not an option to be used as the restriction material directly. Water can also contaminate the nitrogen flow within the microcooler if it is not separated well enough from the channels. [6]

There are several materials which expand when they get colder under certain conditions. This means they have a negative thermal expansion coefficient (NTE). Recently, these materials have been studied a lot and some promising options have been discovered. A small overview can be seen in table 2. The categories refer to the mechanism which causes the NTE: 1 stands for flexible network, which deals with strong atomic bands; 2 stands for atomic radius contraction, which deals with shifts in electron valence bands; 3 stands for magnetovolume effect, which deals with variations of the magnetic moment of a magnetic material. Further information on these topics can be read in Takenaka (2012). [7]

Materials	α (ppm K^{-1})	T_{oper} (K)	Category	Method[a]
β-eucryptite	−1 to −6[b]	300–900	1	D
α-ZrW_2O_8	−9	<425	1	D/N
β-ZrW_2O_8	−6	425–1030	1	D/N
$Cd(CN)_2$	−33.5	170–375	1	X
ReO_3	−0.5	<220	1	N
ReO_3	−0.7	600–680	1[b]	N
$(HfMg)(WO_4)_3$	−2[b]	Room temp. ~ 1070	1	D
$Sm_{2.75}C_{60}$	−100[b]	<30	2	X
$Bi_{0.95}La_{0.05}NiO_3$	−82[b]	320 ~ 380	2	D
Invar (Fe-36Ni)	0.1–1	<500	3	D
Invar (Fe_3Pt)	−6 to −30	100–420	3	D
$Tm_2Fe_{16}Cr$	−9[b]	340–380	3	X
CuO nano particles	−36[b]	<150	3[b]	X
$Mn_3Cu_{0.53}Ge_{0.47}N$	−16	265–340	3	D
$Mn_3Zn_{0.4}Sn_{0.6}N_{0.85}C_{0.15}$	−23	270–335	3	D
$Mn_3Zn_{0.5}Sn_{0.5}N_{0.85}C_{0.1}B_{0.05}$	−30	280–340	3	D

[a] D, dilatometry; N, neutron diffraction; X, x-ray diffraction.
[b] The thermal expansion is anisotropic and α is the averaged value.

Table 2: materials with negative thermal expansion coefficients (derived from Takenaka, 2012 [7])

From the equation for calculating the mass-flow in chapter 3.4 the necessary change in height can be calculated. For the microcooler to get a mass-flow which is ten times as high as the normal massflow, the height of the restriction should increase by $\sqrt[3]{10}$. Since at 100K the restriction should be the original size of 305 nm, this means that at 300K (start of the cool-down) the restriction should be $305 \cdot \sqrt[3]{10} \approx 657$ nm. The NTE material will have to close of the rest of the channel (which is 50 µm in height). To calculate the required NTE value the formula $\Delta l = \alpha \cdot l \cdot \Delta T$ is used. This gives a NTE of $\frac{657 \cdot 10^{-3} - 305 \cdot 10^{-3}}{(300-100) \cdot 49{,}695 \cdot 10^{-6}} \approx 35$ µm/(m·K).

When considering the temperature range of the microcooler and calculating the required NTE value for some desired mass-flow, the best option seems to be cadmium cyanide ($Cd(CN)_2$). And if it is possible, it could be bonded with a layer of cubic zirconium tungstate (α-ZrW_2O_8) to finetune the restriction in the lower temperature region. The problem with this solution is the bonding. Also, the bonding between the cadmium cyanide and the glass will be very difficult, mainly because as the first material expands the glass will contract and huge amounts of stress can be developed. Maybe, some kind of pocket within the glass can be created, in which a piece of the NTE material sits freely. This could be looked into further, but this study will focus on a different design.

When the idea of using hydrogels as a restriction material was discarded, a new idea arose: what if a separate channel was build which could be closed off at the beginning of the CFHX (the warm end). Then the water would remain liquid and because of the temperature profile of the CFHX, the temperature of the cold tip could still be used as the direct control for the mass flow. But adding another channel would mean adding more glass. This will result in more heat flowing from the warm end to the cold tip of the microcooler. So why not create a very short channel near the cold tip which can be closed off by another kind of mechanism. To find out if such a design is possible, ways to (partially) close off a channel should be studied. This leads to the option of micro valves.

A detailed review of different type of micro valves is made by Oh and Ahn (2006) [8]. Of course a lot of research is done and a lot of improvements are made in the field of micro valves since then, but the basic principles stay the same. A summary of the different types of micro valves can be seen in table 3.

Categories			
Active	Mechanical	Magnetic	External magnetic fields
			Integrated magnetic inductors
		Electric	Electrostatic
			Electrokinetic
		Piezoelectric	
		Thermal	Bimetallic
			Thermopneumatic
			Shape memory alloy
		Bistable	
	Non-mechanical	Electrochemical	
		Phase change	Hydrogel
			Sol–gel
			Paraffin
		Rheological	Electro-rheological
			Ferrofluids
	External	Modular	Built-in
			Rotary
		Pneumatic	Membrane
			In-line
Passive	Mechanical	Check valve	Flap
			Membrane
			Ball
			In-line mobile structure
	Non-mechanical		Diffuser
		Capillary	Abrupt
			Liquid triggered
			Burst
			Hydrophobic valve

Table 3: list of different types of microvalves (derived from Oh and Ahn, 2006 [8])

To choose between the different designs of micro valves, the constraints on the design should be taken into account. Because the valve should dissipate as little heat as possible, especially when the system has cooled down to operating temperature, a normally closed valve is most desirable. A good solution is a piezoelectric valve. These valves work through piezoelectric materials that can expand into one direction by supplying a voltage across the material. There are two of those valves that will be elaborated on.

The first is a valve that uses a piezoelectric actuated stepper motor designed by Fazal and Elwenspoek (2007) [9]. A schematic drawing (figure 6) and picture (figure 7) can be found below. This design can switch between multiple states and has the big advantage that it only uses power when it switches between states. The valve itself consists of three wafers. The bottom wafer holds the inlet and the outlet; this wafer can be the same as the top wafer of the microcooler. The middle wafer holds the valve seat and has a static resistance. The top wafer contains the boss, which can be deflected by the piezoactuator above it. This actuator has a metallic pin with screw-thread and as the steppermotor turns, the metalic pin bears down onto the boss. This can be controlled perfectly and the massflow can be decided very acurately. A drawback however is that the Joule-Thomson effect might happen within the valve and the control on the process is lost.

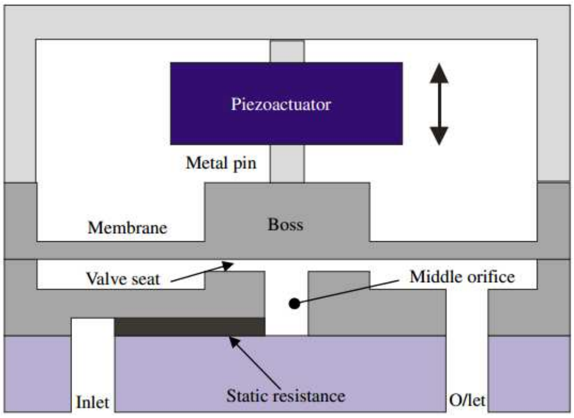


Figure 7: schematic of the piezoelectric actuated stepper motor valve (figure by Fazal and Elwenspoek, 2007 [9])

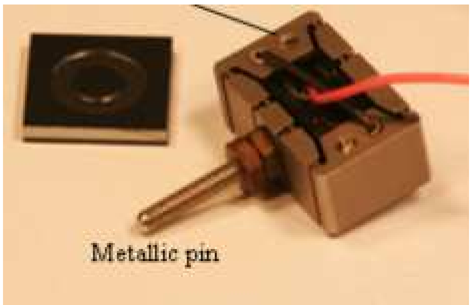


Figure 6: photo of the boss and the stepper motor with metal pin (figure derived from Fazal and Elwenspoek, 2007 [9])

The second piezoelectric micro valve does not have this problem. It is either fully open, or fully closed. The design is from Yang et al. (2004) [10]. A schematic drawing of the design can be seen in figure 8. The design once again consists of an inlet and outlet, a valve seat, a boss and a way to bear down onto the boss to close the valve. A small difference is that the boss does not separate the working fluid from the rest of the system, but housing is built around the entire valve. A cross-section can be found in figure 9.

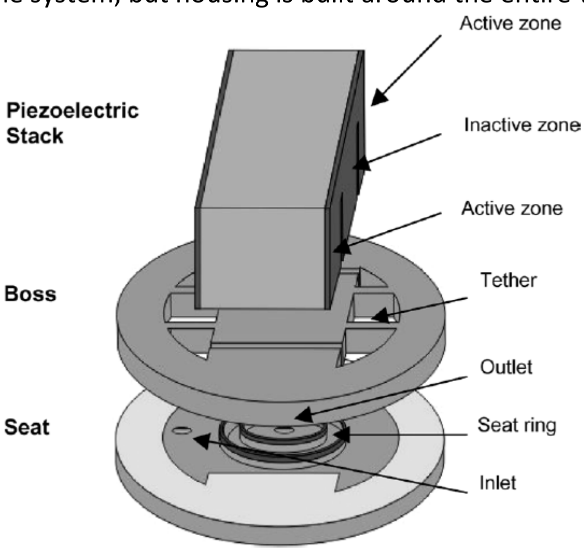


Figure 8: schematic of the piezoelectric stack valve (figure by Yang et al., 2004 [10])

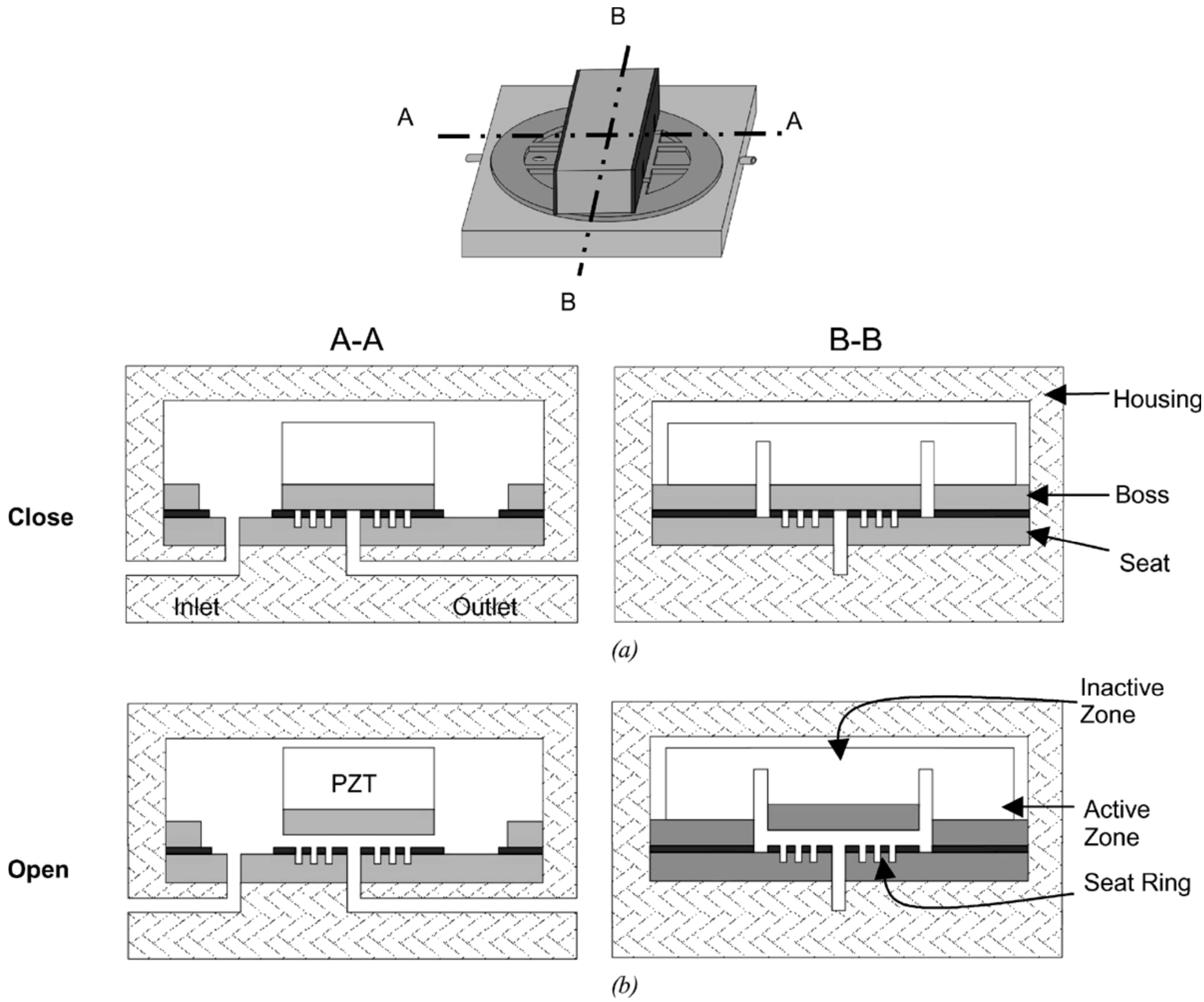


Figure 9: cross-sections of the piezoelectric stack valve (figure by Yang et al., 2004 [10])

The figure above displays two cross-sections of the valve (A-A and B-B) and shows them in the closed position (a) and in the open position (b). The piezoelectric material is put into stacks in the 'active zone' of the valve system and is at the sides of the boss. The boss itself is connected to the material above it, the 'inactive zone'. The inactive zone is connected to the active zone through a bridge and when the active zone expands (by applying a voltage on the piezoelectric material) this inactive zone is pushed upwards. The valve is opened. To maintain the voltage of 60V on the piezoelectric stacks a small power of 3 mW is needed. When the voltage is decreased again, the stacks contract again and the inactive zone pushes the boss on the valve seat and the valve is closed.

6.3 Integrating the solutions with the microcooler

These two solutions, which use piezoelectric material, can easily be implemented with the current design, by adding the valve on top of the microcooler. This study does not deal with detailed fluid dynamic like pressure variance within the channel. So the decision to make the design symmetrical is purely intuitive.

In figures 10 and 11 crude schematic drawings can be found of the designs. Figure 10 shows the design with the stepper motor and figure 11 shows the design with the stacks. At the top of the drawings the valve seat is shown from above, with the dashed circle representing the seat rings. Below this a top view of the end of the high-pressure channels is shown, with the dashed circle being the place of the valve ontop of it. To the right the front view of the restrictions are shown.

The idea is that the valves are open during cool-down time and will be closed when the temperature nears the operating temperature.

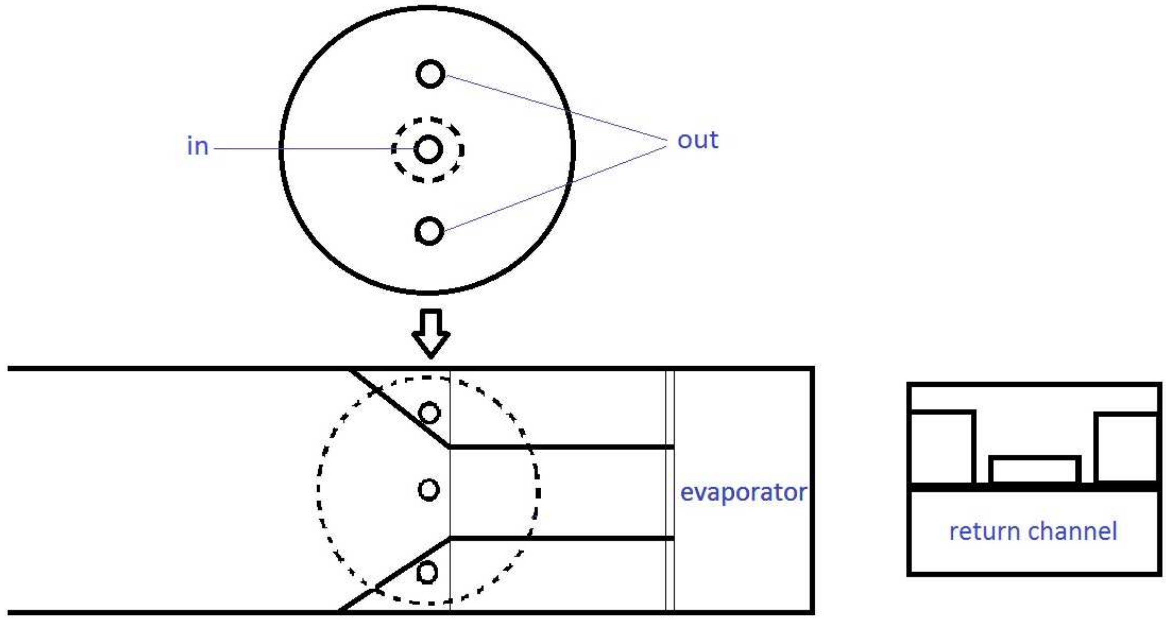


Figure 10: schematic of a microcooler design with a valve operated by a piezoelectric stepper motor

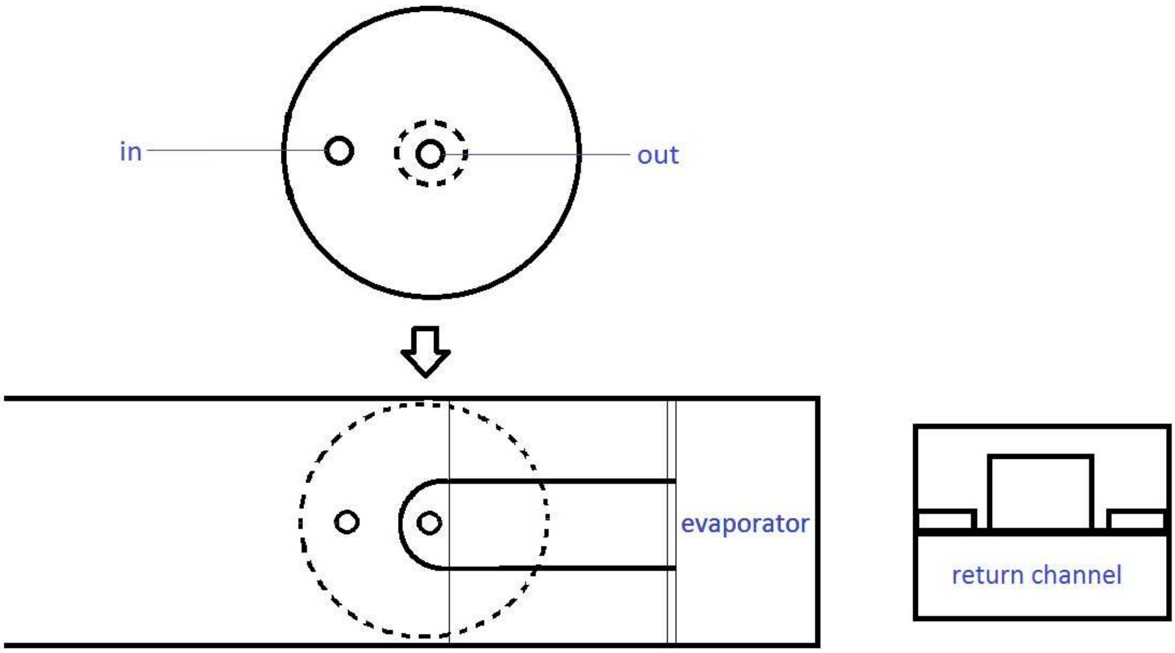


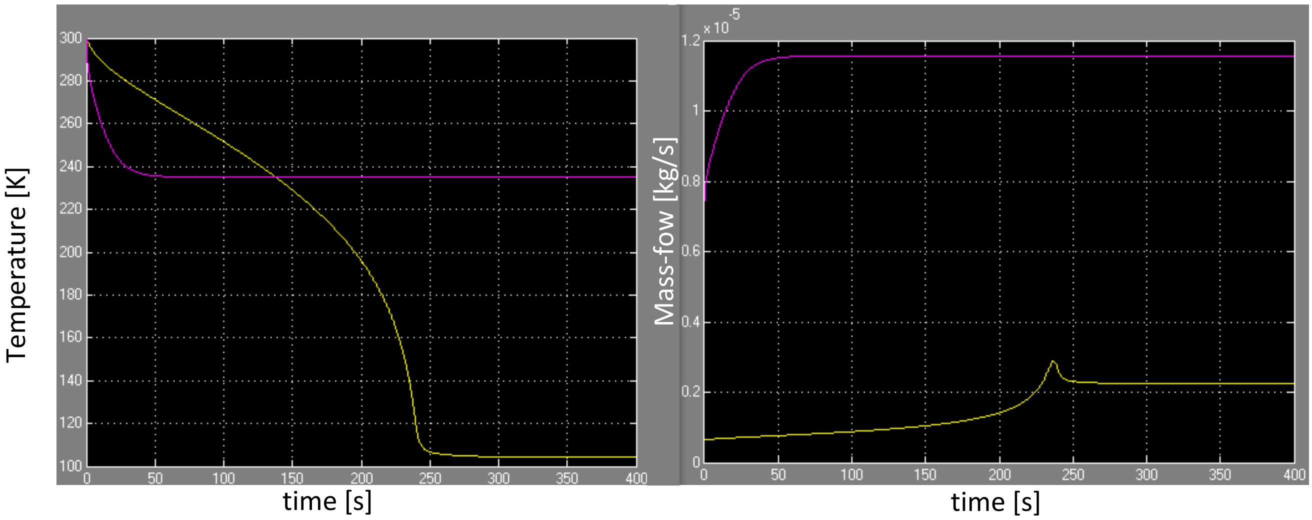
Figure 11: schematic of a microcooler design with a valve operated by piezoelectric stacks

6.4 Model results

To test this design the model was adjusted to incorporate the changes. For the restriction the dimension used can be found in table 4. The results are shown in graph 4.

Channel	Close-off temperature [K]	Height [nm]	Width [µm]	Length [µm]
solid	*never*	390	950	140
closable	120	858	950	140

Table 4: dimensions of the restrictions in the new design



Graph 4: old and new cool-down with corresponding mass-flows

The purple line shows the new design. The left graph shows the temperature of the cold tip and the right graph shows the mass-flow.

These results show that the cold tip never cools down to the desired temperature. This is because there actually is too much mass-flow and the CFHX can longer cool all the fluid running through it as efficient. So the original assumption that more mass-flow is always better does not hold. In the beginning however the temperature decreases very rapidly, so there is some merit to this design. However, a new design should be considered.

7 A Design with Multiple Closable Channels

7.1 The new design

In the previous chapter it was shown that by increasing the mass-flow too much, the system will not reach the operating temperature. But in the first moments the temperature decreases much faster than in the original design. The design with the stepper motor could be adjusted to switch between states at the right moments, but, as was said before, the Joule-Thomson expansion might happen at the wrong place. This leads to the decision of creating multiple channels, which can be closed off separately. Through trial and error and bearing in mind that more channels lead to overcomplicated designs, the following solution is found: the restriction will be divided into four channels. One channel is always open and has the same mass-flow as the original design. The other channels can be closed off by using the micro-valve design discussed in the previous chapter with piezoelectric stacks. The valve system has one inlet channel and three outlet channels (one for each extra restriction channel). The three outlet channels are closed by three separate piezoelectric stacks.

A schematic drawing of the design is shown in figure 12. This drawing is not to scale and it only shows the characteristic aspects of the microcooler.

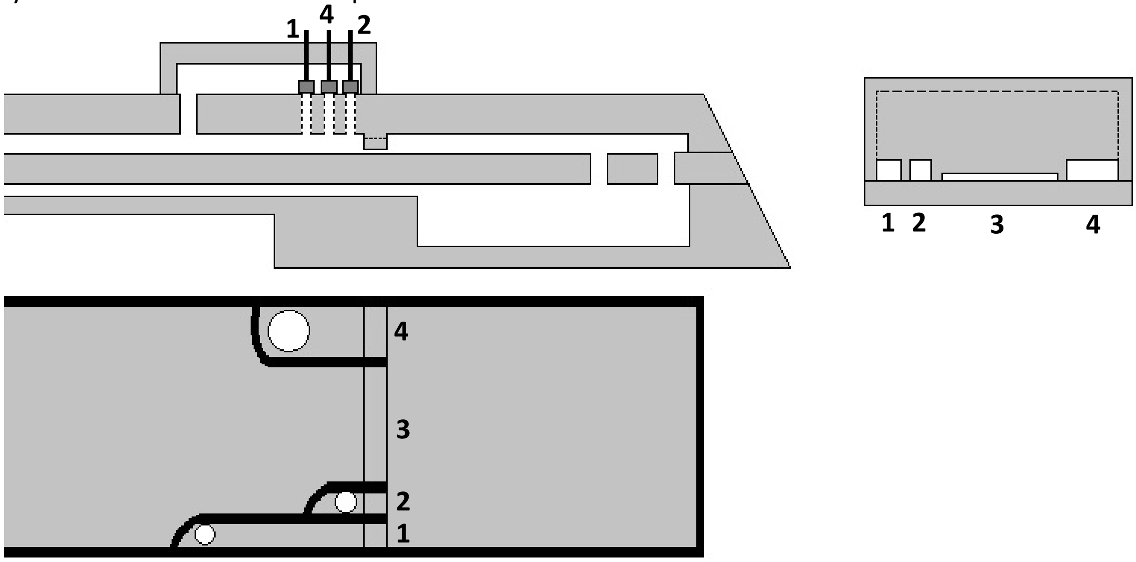


Figure 12: schematic of the microcooler design with multiple closable channels

At the top left is a view from the side of a cross-section along the length of the microcooler, which shows the external valve system. At the bottom left is a view from the top of a cross-section along the length of the microcooler. It shows the end of the high-pressure channel. The thick black lines represent glass walls and the thin vertical lines show the place of the restriction. To the top right a part of a cross-section along the width of the microcooler is shown. The low-pressure channel and bottom wafer are left out. This cross-section is taken at the place of the restriction. The dashed line shows the size of the high-pressure channel behind it.

The dimensions of the channels, numbered from left to right in the front view, and the temperature at which they should be closed are as follows in table 5:

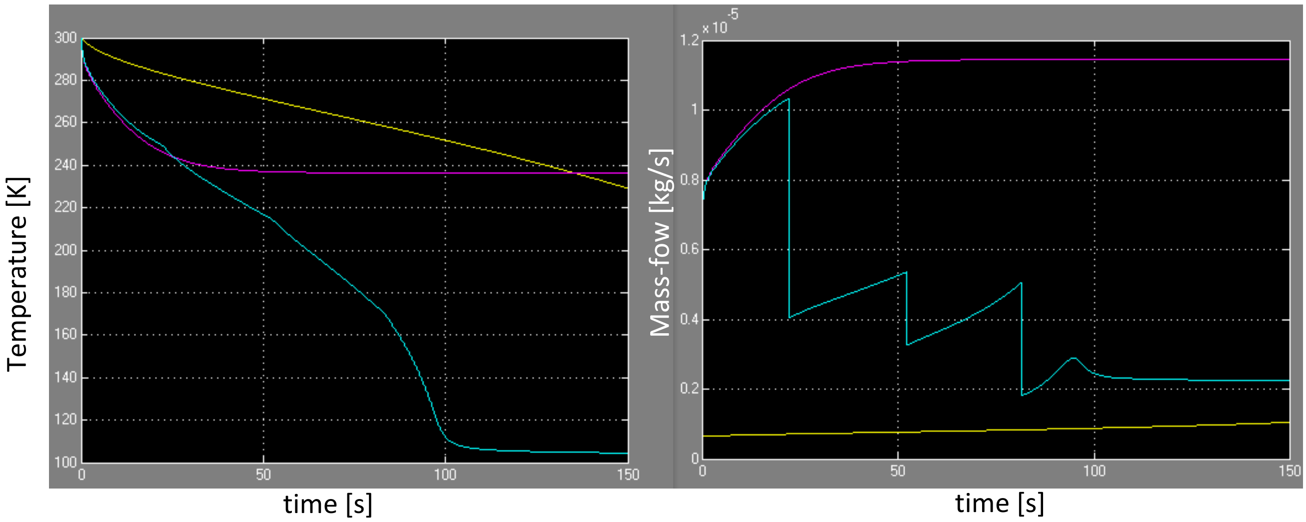
Channel	Close-off temperature [K]	Height [nm]	Width [μm]	Length [μm]
1	215	1000	100	140
2	170	1000	100	140
3	*never*	372	1100	140
4	250	1000	400	140

Table 5: dimensions of the restrictions in the new design

The glass walls separating the channels are each 0,1 mm in width. This brings the total width of the channels to the same 2 mm of the high-pressure channel.

7.2 Model results of the new design

When modelling this design, the results in graph 5 are obtained. The purple graph is the design with only one valve and the yellow line is still the original design. The blue line is the new design. During the beginning of the cool-down, the new design and the design with only one valve are not exactly the same, this is because the three valves generate more heat to stay open than just one valve. To the right are the corresponding mass-flow rates. The effect of closing the channels on the mass-flow rate can be seen clearly.
As can be read from the model results, the new design cools down about three times as fast as the original design.



Graph 5: cool-down and corresponding mass-flow of the old design, the design with one valve and the new design

8 Conclusion

The aim of this study was to find an answer to the research question: how can the restriction of a Joule-Thomson microcooler be manipulated to decrease the cool-down time of this cooler, without effecting the working of the cooler once it has cooled down?

The model created for this study shows that manipulating the restriction of the current Joule-Thomson microcooler indeed results in a faster cool-down time. There are several ways to manipulate the restriction for this cause, but not all of them work. The best option proposed in this study works very well: the cool-down time is decreased by introducing three extra channels at the restriction, which can be closed separately. They can be closed by the use of valves on top of the microcooler. These valves are normally closed and can be opened by applying a voltage to piezoelectric stacks. These stacks expand and will lift the cover from the outlet hole of the valve system, allowing gas to flow through. All three extra channels have their own restriction at the end. At the beginning of the cool-down period all valves are open and maximum mass-flow is obtained. When a certain temperature is reached a valve closes; this happens three times until only one open channel remains, which has the same mass-flow as the channel in the original design. By using this design the cool-down time of the microcooler can be made three times as short.

It is recommended that the new design is built, tested and further studied. Also, a design which incorporates a material with a negative thermal expansion coefficient as the restriction should be studied.

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