Method to characterize a thermal diode in saturated steam atmosphere

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We present a novel measurement method for the characterization of thermal diodes in a saturated steam atmosphere. A measuring setup has been developed in which two pressure sensors are integrated. Using a developed analytical model, the heat flow, the volume flow and the cracking pressure are determined from the measured absolute pressures and the pressure difference. The analytical model was verified using a flow through an orifice. We first calculated the volume flow through the orifice, with a diameter of 3 mm, using the Reader-Harris equation and then compared it to experimentally determined values. The experimentally values showed a discrepancy of 9%. With the measurement setup, we have characterized a check valve developed for magnetocaloric heat pumps, which has a thermally rectifying behavior. The developed check valve consists of three spring arms, which are radially attached to a valve disk. The heat flow through the check valve in forward direction is 166 W for water, 239 W for ethanol and 547 W for methanol at a temperature difference of 1 K. In the reverse direction, the heat flow is -0.03 W at a temperature difference of -1 K. For methanol, this corresponds to a rectification coefficient of more than 18,000.

I. INTRODUCTION

In the context of energy transition, the control of heat transport is a central challenge. In many technical applications, such as energy conversion systems[1], heating or cooling technology[2,3] and heat management[4], the rectification of a heat flow is an essential component. Thermal diodes are used for this task. As a result, heat provided by oscillating heat sources can be utilized more efficiently[5]. Analogous to the electric diode; the thermal diode has a lower thermal resistance in forward direction than in reverse direction. The thermal resistance is defined as the ratio of the temperature difference between heat source and sink and the heat flow.

Besides anisotropic solids[6] or thermosiphons[7], check valves can be used as thermal diodes under certain conditions[8]. They are used in pumping systems[9,10] or especially in a saturated steam atmosphere like in gas compressors[11,12]. Check valves are also used in the automotive sector to support heat management in a saturated steam atmosphere, as it is found in a heat pipe[13]. Latent heat as type of heat transfer, the check valve corresponds to a fluidic diode in addition to the thermal diode. The fluidic resistance is defined as the ratio between the pressure difference (upstream and downstream) and the volume flow.

Parameters such as cracking pressure, heat flow or volume flow in the forward and reverse direction characterize check valves. The efficacy of check valves is given by the rectification coefficient, which means the difference between the heat flow in forward and reverse direction in relation to the heat flow in reverse direction[14]. It is obvious that there is a need of knowledge concerning the check valves parameters in order to employ it in an efficient way. Therefore, it is important to measure under operating conditions e.g. in a saturated steam atmosphere.

Check valves are usually characterized in liquid phase with pressure sensors or flow meters, which limit the choice of fluid due to their mode of operation[15]. In order to use flow meters, the fluid has to have for example a certain electrical conductivity or a certain viscosity. Moreover, some fluid densities in a saturated steam atmosphere are too low as to be characterized by a flow meter. For this reasons are the mentioned methods not sufficient for the characterization of a check valve in saturated steam atmosphere. Simulations can support experiments, however due to their complexity they cannot replace the measurement[16,17].

We present a measuring method for the characterization of check valves in a saturated steam atmosphere. Two pressure sensors measure the check valve properties dynamically. A single pressure surge in both, the forward and reverse direction, is sufficient for the characterization. Furthermore, we introduce an analytical model for the determination of the volume flow and the heat flow based on the measured pressures. In order to introduce the measuring method, we developed a check valve which is suitable for the use in a caloric heat pump[3,18]. The analytical model is then verified by comparing the experimental results of an orifice with the analytical results from the Reader-Harris equation[19,20].

II. METHOD AND MATERIAL

We determine the volume flow $\dot{V}$, the heat flow $\dot{Q}$ and the cracking pressure p_{cracking} of the check valve with one pressure surge in forward and one pressure surge in reverse direction. From the pressure gradient the differential pressure dependent volume flow $\dot{V}(\Delta p)$ is calculated and from the volume flow the temperature dependent heat flow $\dot{Q}(\Delta T)$. From the fluid-dependent measurement, volume flow and heat flow can be converted for any fluid. We develop a check valve and characterize it with our measuring method. Using the Reader-

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Harris equation[19,20] the diameter of the flow area through the check valve is determined, assuming that its geometry is similar to an orifice.

A. Theoretical Methods

The time-dependent pressure gradient $\dot{p}$ is determined from the pressure p of the downstream flow of the check valve into the constant chamber volume V_0. From $\dot{p}$ we calculate the volume flow $\dot{V}$ through the check valve. To determine the volume flow, the following assumptions are made: The fluid is present in a saturated steam atmosphere. The gaseous part of the fluid behaves like an ideal gas and the pressure is homogeneous in the respective closed areas (see Fig. 1). Quantitatively, under these assumptions, the volume flow $\dot{V}$ can be described as the time derivative of the ideal gas law:

$$\dot{V}(\Delta p) = \frac{M \cdot V_0}{\rho \cdot R \cdot T} \cdot \dot{p}(\Delta p). \tag{1}$$

$\dot{p}$ and therefore $\dot{V}$ depend on the pressure difference Δp, before and after the check valve. If the check valve is constructed similar to an orifice, which means a constant and a circular diameter, the flow coefficient of the check valve $C_{\text{check valve}}$ can be approximated by the flow coefficient of the orifice C_{orifice}. C_{orifice} can be determined with the Reader-Harris equation[19,20]:

$$C_{\text{orifice}} = 4\frac{\dot{V}_{\text{orifice}} \cdot \sqrt{1-\beta^4}}{\varepsilon \cdot d^2_{\text{orifice}} \cdot \pi}\sqrt{\frac{\rho}{2 \cdot \Delta p}}, \tag{2}$$

where $\dot{V}_{\text{orifice}}$ corresponds to the volume flow through the orifice, β to the ratio of the pipe diameter to the inner diameter of the orifice, ε to the expansion number of the fluid, d_{orifice} to the inner diameter of the orifice, Δp to the pressure difference upstream and downstream of the orifice, and ρ to the density of the fluid. The ratio $\frac{C_{\text{orifice}}}{\sqrt{1-\beta^4}}$ is called flow number α.

With C_{orifice} and the measured volume flow through the check valve $\dot{V}_{\text{check valve}}$ the diameter $d_{\text{check valve}}$ of the flow area of the check valve can also be defined. Assuming that the pipe diameter is much larger than the inner diameter of the orifice ($\beta = 0$) and that it is an incompressible fluid ($\varepsilon = 1$), Eq. 2 can be converted to $d_{\text{check valve}}$ as follows:

$$d_{\text{check valve}} = 2 \cdot \sqrt{\frac{\dot{V}_{\text{check valve}}}{\pi \cdot C_{\text{orifice}}}\sqrt{\frac{\rho}{2 \cdot \Delta p}}}. \tag{3}$$

To determine $\dot{V}$ for a second fluid (from now on with the index 2), but without having taken the measurement, one uses the fact that the diameter of the check valve doesn't depend on the fluid. With the help of an already calculated volume flow (from now on with the index 1) and using Eq. 3 the volume flow $\dot{V}_2$ can be calculated:

$$\dot{V}_2 = \dot{V}_1 \cdot \sqrt{\frac{\Delta p_2 \cdot \rho_1}{\Delta p_1 \cdot \rho_2}}. \tag{4}$$

From Δp_1 at a certain density ρ_1 the pressure difference Δp_2 is formed, which depends on the density ρ_2 of the second fluid.

The thermal heat flow $\dot{Q}$, which depends on the temperature difference ΔT before and after the check valve, can be calculated with $\dot{V}$, ρ, and the latent heat L.

$$\dot{Q}(\Delta T) = \dot{V}(\Delta T) \cdot \rho \cdot L. \tag{5}$$

B. Measuring Method

The measuring setup for characterizing of the check valve consists of a metal pipe system suitable for vacuum, schematically shown in Fig. 1.

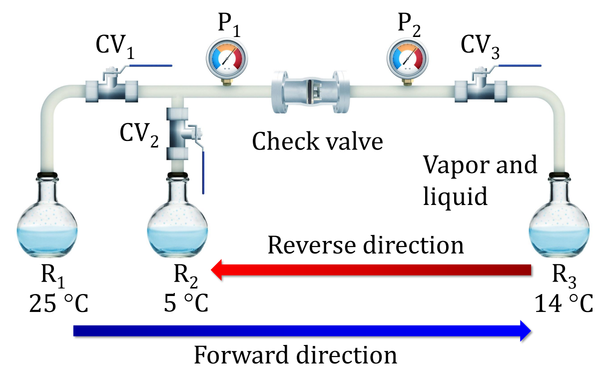

FIG. 1. Scheme of the measurement setup for the characterization of check valves in a saturated steam atmosphere. The pressure is measured upstream P_1 and downstream P_2 of the check valve. The reservoirs R_1, R_2 and R_3 contain liquid with different temperatures ($T_{R_2} < T_{R_3} < T_{R_1}$). The control valves CV_1, CV_2 and CV_3 can be used to induce pressure surges in the forward and reverse direction.

The pipe system has three reservoirs (R_1, R_2 and R_3) each with a control valve (CV_1, CV_2 and CV_3). The pressure is measured upstream with a pressure sensor P_1 and downstream with P_2. The check valve is installed between P_1 and P_2. Two absolute pressure sensors MPX2100AP from Freescale Semiconductor with a range of 0 mbar-1000 mbar are used, which operate piezo resistively. The signal of the sensors is amplified 51 times with an operational amplifier INA111. The pressure data is recorded using DAS801 by Sefram.

The pipe system is evacuated to a pressure of < 1 mbar. Afterwards, the reservoirs are filled with degassed ethanol (removal of non-condensable fluids). The entire setup, except for the reservoirs, is heated to 45 °C to ensure that the liquid part of the fluid is only in the reservoirs. The saturated steam pressure in the system leads to a linked temperature and pressure (ideal gas law with constant volume). The ethanol in the three reservoirs is tempered to 25 °C in R_1, 5 °C in R_2 and 14 °C in R_3. The different temperatures of the ethanol in the reservoirs result in a compensating gaseous volume flow through the check valve. The control valves CV_1, CV_2 and CV_3 control the pressure surges, which in turn cause the volume flow. The check valve is alternately subjected to pressure surges in the reverse and forward direction.

C. Check Valve for Saturated Steam

We developed and manufactured a check valve with which the measuring method was tested[21,22]. The check valve was developed for use in a magnetocaloric heat pump according to the specifications made in Bartholomé *et al.* As mentioned by Bartholomé *et al.* the magnetocaloric heat pump consist of magnetocaloric material, which is located in a heat pipe. The magnetocaloric material is cyclically magnetized and demagnetized, which leads to heating respectively cooling of the material. The heat transfer fluid in the heat pipe ensures heat transfer via latent heat from the heat exchangers to the caloric material. Using check valves a directed heat flow is generated by means of the condensation and evaporation of the fluid.

The check valve has been designed to achieve a rectification coefficient of at least 100. The aim was also to achieve a low cracking pressure in the forward direction.

In Fig. 2 the developed check valve is shown. The etched check valve (1) consists of a valve disk (copper beryllium, 2.1247, with a thickness of 50 µm), on which three meander-shaped spring arms are symmetrically attached (Fig. 2A). The spring arms are attached to the orifice like valve seat (5-7) including a stroke catcher (2-4) (Fig. 2B). Both the valve seat and the stroke catcher are made of polyether ether ketone. A pressure surge in the forward direction causes the valve disk to deflect. If a pressure surge occurs in the reverse direction, the valve disk closes the valve seat via the sealing ring (Fig. 2C). The stroke catcher is intended to prevent plastic deformation of the valve disk in the event of a pressure surge. The thermal mass of the check valve was chosen to be particularly small (< 10 J/K) in order to have as little effect as possible on the application in which they will be employed.

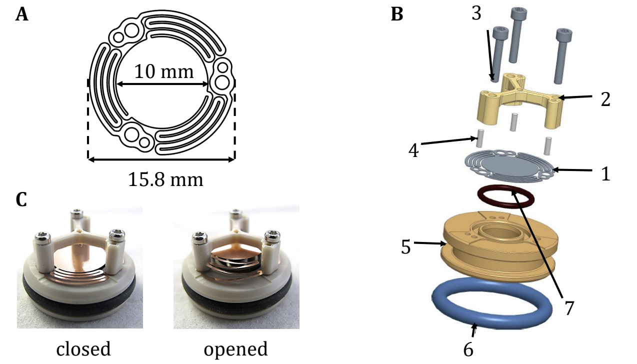

FIG. 2. The developed check valve. **(A)** Drawing of the valve disk. Three spring arms are radially attached to the valve disk. **(B)** In addition to the valve disk (1), the check valve consists of a valve seat (5-7) and a stroke catcher (2-4). **(C)** Left; Closed state: The valve disk closes the valve seat. Right; Open state: The valve disk is deflected bounded by the stroke catcher.

III. RESULTS AND DISCUSSION

We have developed a check valve, which has been characterized with the presented measuring method. For this purpose it has been installed in the measuring setup (Fig. 1) in which a saturated ethanol vapor atmosphere has been generated. The check valve has been subjected to pressure surges in the forward and reverse direction.

A. Verification of the Analytical Model

To verify the model, the volume flow of an orifice with an inner diameter of 3 mm and a thickness of 6 mm, is calculated analytically using the Reader-Harris equation[19]. The orifice was measured using ethanol as fluid with the presented measuring method and the resulting volume flow was determined. The analytically calculated volume flow and the measured volume flow are then compared. The pipe system in which the orifice is installed has an inner diameter of 25 mm. The ratio of the orifices inner diameter to the pipe diameter is $\beta = 0.12$.

Two assumptions are made for simplification. The first assumption is $\beta = 0$, instead of $\beta = 0.12$. The flow number α thus only consists of the flow coefficient C. Based on Reader *et al.*, this assumption results in $\alpha = 0.5961 \approx 0.6$[20]. The expansion number ε for ethanol is $1.0 < \varepsilon \leq 1.1$ for 0 mbar $< \Delta p \leq 23.5$ mbar, according to ISO 5167-2[19]. Therefore the second assumption is $\varepsilon = 1$.

The Reader-Harris equation applies to a ratio of orifice thickness to orifice diameter of ≤ 0.1. In this setup the ratio is 2, resulting in a flow coefficient which is estimated to be 30% larger than $C = \alpha = 0.6$, following Reader *et al.*[23]. The flow number α thus shifts from 0.6 to 0.8. The shifted flow number $\alpha = 0.8$ is also assumed for the check valve (see Fig. 7). In Fig. 3 both the measured flow rate with ethanol and the values calculated according to Reader-Harris with a α of 0.6 and of 0.8 through an orifice are shown.

It is evident that the measured values lie between the two calculated volume flows. The analytical model is therefore verified with a given uncertainty of 9%. The measuring method is well suited to characterize various check valves in a saturated steam atmosphere.

B. Cracking Pressure and Data Selection

Fig. 4 shows how the cracking pressure and the volume flow in the forward and reverse direction are determined. The pressures p_1 upstream and p_2 downstream of the check valve are shown. Only four time ranges (*I-IV*, highlighted) are relevant:

- Area *I* (green): Only CV_1 is open, which means that the pressure upstream and downstream corresponds to

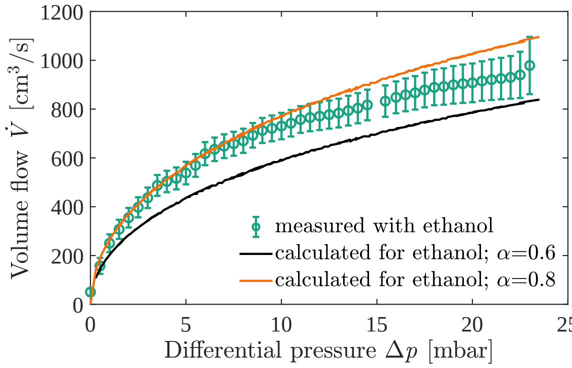

FIG. 3. Measured (dots) and calculated volume flow (solid line) with Gaussian error propagation of ethanol vapor through a 3 mm orifice. The volume flows were calculated using the Reader-Harris equation, with a flow number of 0.6 and a shifted and estimated flow number of 0.8.

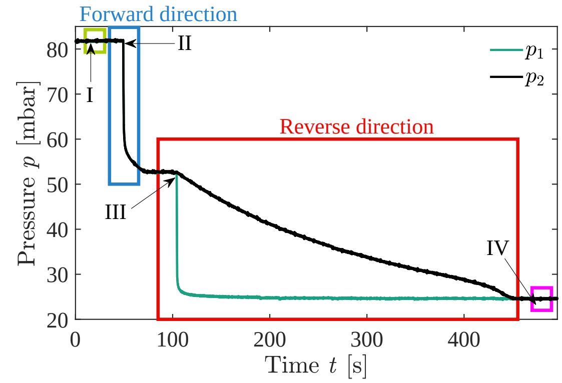

FIG. 4. Raw data of pressures, upstream and downstream of the check valve. In area *I* the cracking pressure is determined, only CV_1 is open. In area *II*, the volume flow in forward direction is determined (only CV_3 is open) and in area *III* the volume flow in reverse direction is determined (only CV_2 is open). In area *IV* the pressure offset between p_1 and p_2 is determined. Only CV_3 is opened for this purpose.

the temperature of R_1. The cracking pressure of the check valve is determined from the data in this area (see Fig. 5).

- Area *II* (blue): Only CV_3 is open. The volume flow in forward direction is determined from the measured data in this area.

- Area *III* (red): Only CV_2 is open, the pressure upstream (p_1) is determined by the temperature in R_2. The volume flow in the reverse direction is determined from the recorded data in this area. p_1 approaches p_2 which means the check valve does not close completely and a volume flow in reverse direction occurs.

- Area *IV* (pink): Only CV_3 is open. From the data in this area the pressure offset between p_1 and p_2 is determined (see Fig. 5).

Figure 5 shows the pressure data of p_1 and p_2 from which the cracking pressure p_{cracking} is determined. The cracking pressure (Fig. 5A) which is still subjected to a pressure offset $\Delta p = p_1 - p_2$ (Fig. 5B) is determined. The difference (A)−(B) results in a p_{cracking} which is below the resolution limit of the sensors of < 1 mbar.

In addition to the parameters already mentioned, other factors are also important for the application, such as in a caloric heat pump. The long-term stability of the check valves has not been specifically investigated, but the check valves in current use in a magnetocaloric heat pump show no signs of fatigue at over 1,000,000 cycles. The measurements also show that the check valve requires ≈ 10 ms to open.

C. Volume Flow

Figure 6 shows the average volume flow from the applied pressure surges in the forward and reverse direction. The error was determined here and for all remaining figures with Gaussian error propagation, estimating an error for V_0 of 5% and for $\dot{p}$ of the standard deviation of at least three measurements. Ethanol was used as the flowing fluid at an average temperature of 22 °C at the position of the check valve. Further shown in Fig. 6 are the calculated volume flows for methanol and water at the same temperature (see Eq. 4 with fluid parameters from the database of the National Institute of Standards and Technology[24]).

The volume flow in forward direction at a pressure difference of 5 mbar is 1750 cm^3/s for methanol, 2270 cm^3/s for ethanol and 5560 cm^3/s for water. The volume flow in the reverse direction, plotted above the negative pressure difference, is −0.3 cm^3/s for methanol, −0.1 cm^3/s for ethanol and −0.2 cm^3/s for water at a pressure difference of −5 mbar.

Using a estimated flow number α of 0.8 after Reader *et al.*[23] in Eq. 3 (see Fig. 3, for $\beta = 0$) the flow diameter of the check valve can be calculated. In Fig. 7 the diameter of the flow area of the check valve ($d_{\text{check valve}}$) normalized to the diameter of the valve seat (d_{orifice}) is shown.

This results in a normalized diameter of 1 above a pressure difference of 2.5 mbar. It can be assumed that from this pressure onwards, the valve disk is completely deflected from the valve seat. The volume flow is now only limited by the valve seat and no longer by the valve disk.

D. Heat Flow

Using the volume flow, the pressure difference, and the fluid parameters from National Institute of Standards and Technology[24] the corresponding heat flow and temperature difference is calculated (Eq. 5, Fig. 8). At a temperature difference of 1 K before and after the check valve, a heat flow of 166 W for water, a heat flow of 239 W for ethanol and a heat

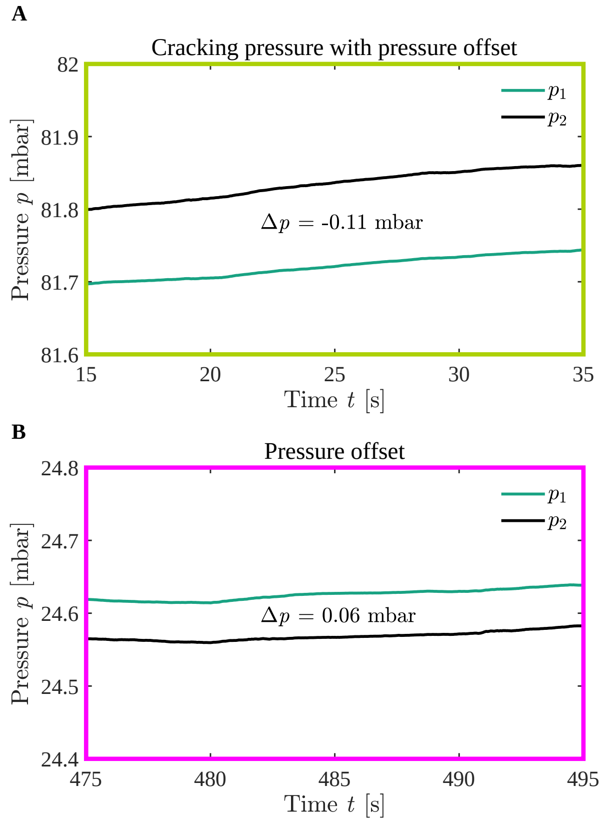

FIG. 5. Section of the raw data (Fig. 4) of the pressures p_1 upstream and p_2 downstream for the determination of the cracking pressure. **(A)** The cracking pressure of the check valve is -0.11 mbar. The value is subject to pressure offset. **(B)** The pressure offset between the sensors is 0.06 mbar. The corrected cracking pressure is the difference between (A)−(B) and is below the resolution limit of the sensors of < 1 mbar.

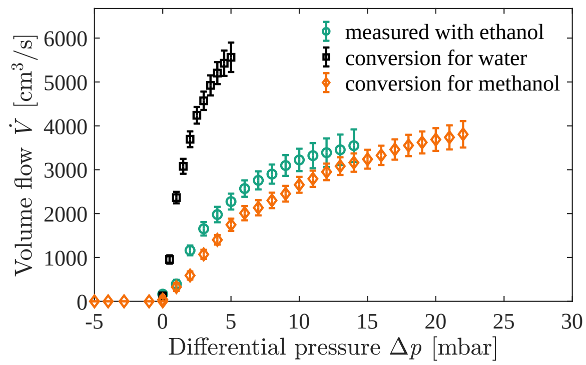

FIG. 6. Calculated volume flow with Gaussian error propagation from the measured pressure gradient for ethanol in both forward and reverse direction through the check valve. From the ethanol measurement the volume flow for methanol and for water was calculated according to Eq. 4.

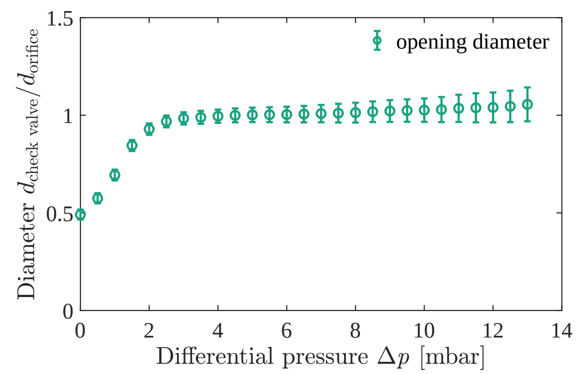

FIG. 7. Determined diameter of the flow area through the check valve with Gaussian error propagation. The diameter is normalized to the diameter of the valve seat (d_{orifice}). The check valve is completely open from 2.5 mbar and the diameter of the flow area corresponds to the diameter of the valve seat.

flow of 547 W for methanol result. The heat flow is dependent on the steam pressure gradient of the gaseous fluid and on its latent heat. A high steam pressure gradient leads to a large heat flow ($\dot{Q} \propto \rho$). Water has a higher latent heat and volume flow than methanol and ethanol, but due to its low steam pressure gradient the heat flow for water is lower. The heat flow in the reverse direction at a temperature difference of -1 K is -0.01 W for water and ethanol and -0.03 W for methanol. Thus, a temperature difference of 1 K results in a rectification coefficient > 18,000 for methanol. In addition with a cracking pressure of < 1 mbar, this check valve is very well applicable for use as a thermal diode.

The developed check valve has a 10 times higher heat flow in forward direction compared to a commercially available silicone check valve with a maximum diameter of 12.6 mm (Duckbill Check Valve from Vernay, part number: V288310100).

IV. CONCLUSION

We have introduced a new measuring method, which allows a characterization of check valves in a saturated steam atmosphere. Only two pressure sensors are required for the whole characterization. We have verified the analytical model by means of an orifice and using the analytical Reader-Harris equation with an error of less than 9%. The measuring method proved to be well applicable to characterize check valves in saturated steam atmospheres. With the measuring method and an analytic model, we have determined the volume flow, the area diameter of the volume flow, the heat flow, and the cracking pressure for a self-developed check valve.

We have calculated the check valves volume flow in forward direction at a differential pressure of 5 mbar. The volume flow has been 1750 cm^3/s for methanol, 2270 cm^3/s for ethanol and 5560 cm^3/s for water. The volume flow in the re-

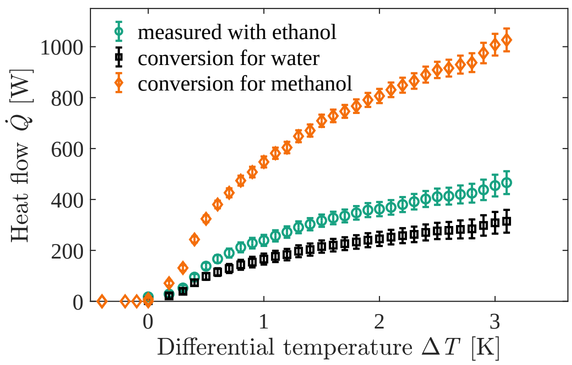

FIG. 8. From the volume flow through the check valve, the heat flow with Gaussian error propagation for water, ethanol and methanol is calculated at an average temperature of 22 °C.

verse direction has been $-0.3\,\mathrm{cm^3/s}$ for methanol, $-0.1\,\mathrm{cm^3/s}$ for ethanol and $-0.2\,\mathrm{cm^3/s}$ for water at a pressure difference of -5 mbar. The cracking pressure has been below the sensors resolution limit of < 1 mbar. We have measured a heat flow of 166 W for water, 239 W for ethanol, and 547 W for methanol at a difference in temperature of 1 K. The heat flow in the reverse direction at a temperature difference of -1 K has been -0.01 W for water and ethanol, and -0.03 W for methanol. Due to a rectification coefficient of $> 18{,}000$ for methanol, the check valve is well suited as a thermal diode.

With the presented measuring method, check valves can be characterized and used in an optimized form. They may be installed in a gas phase or a saturated steam atmosphere, such as is present in a heat pipe. As thermal diodes, check valves can passively rectify a heat flow. This enables efficient energy conversion systems to be developed.

AVAILABILITY OF DATA

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ACKNOWLEDGMENTS

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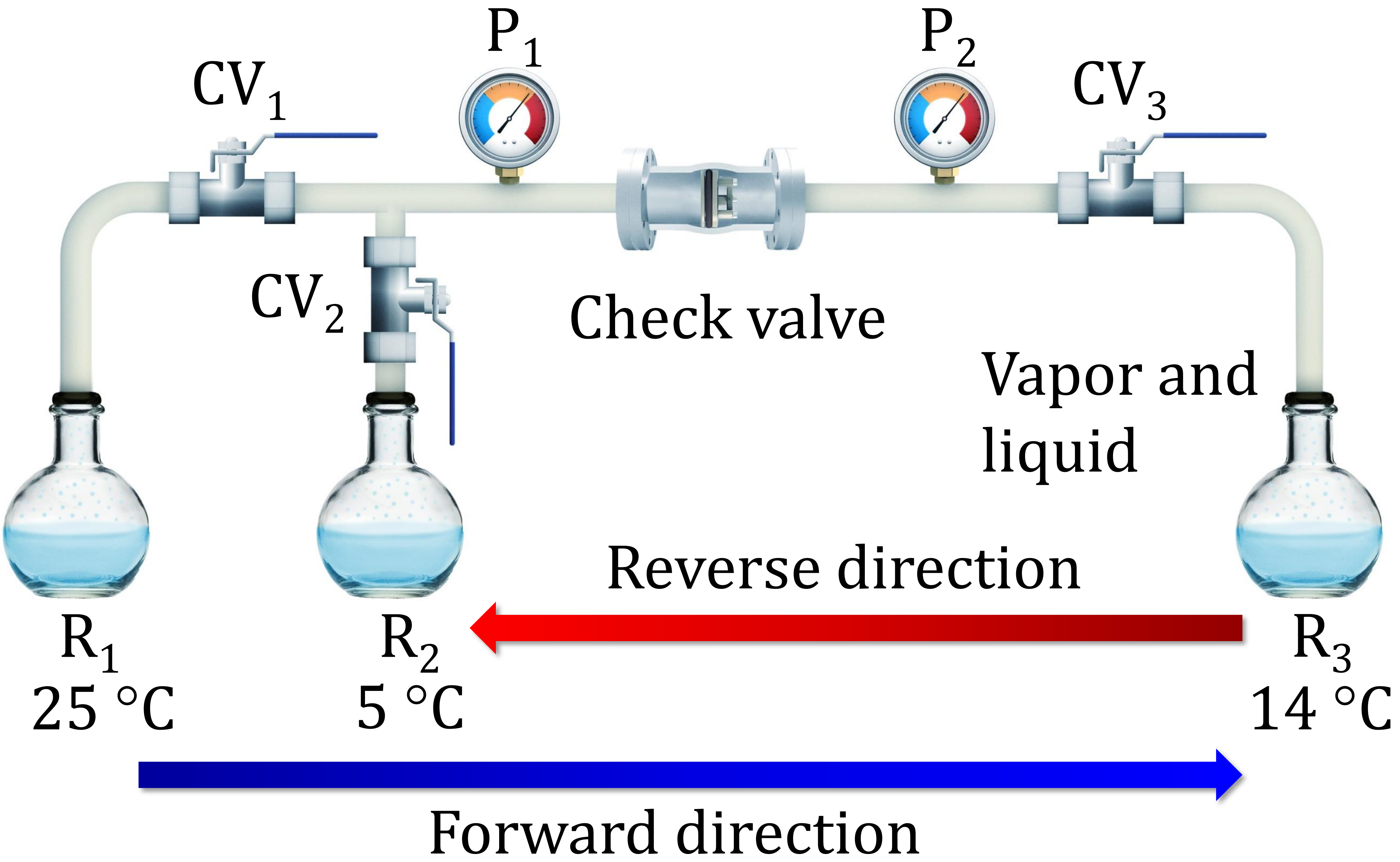
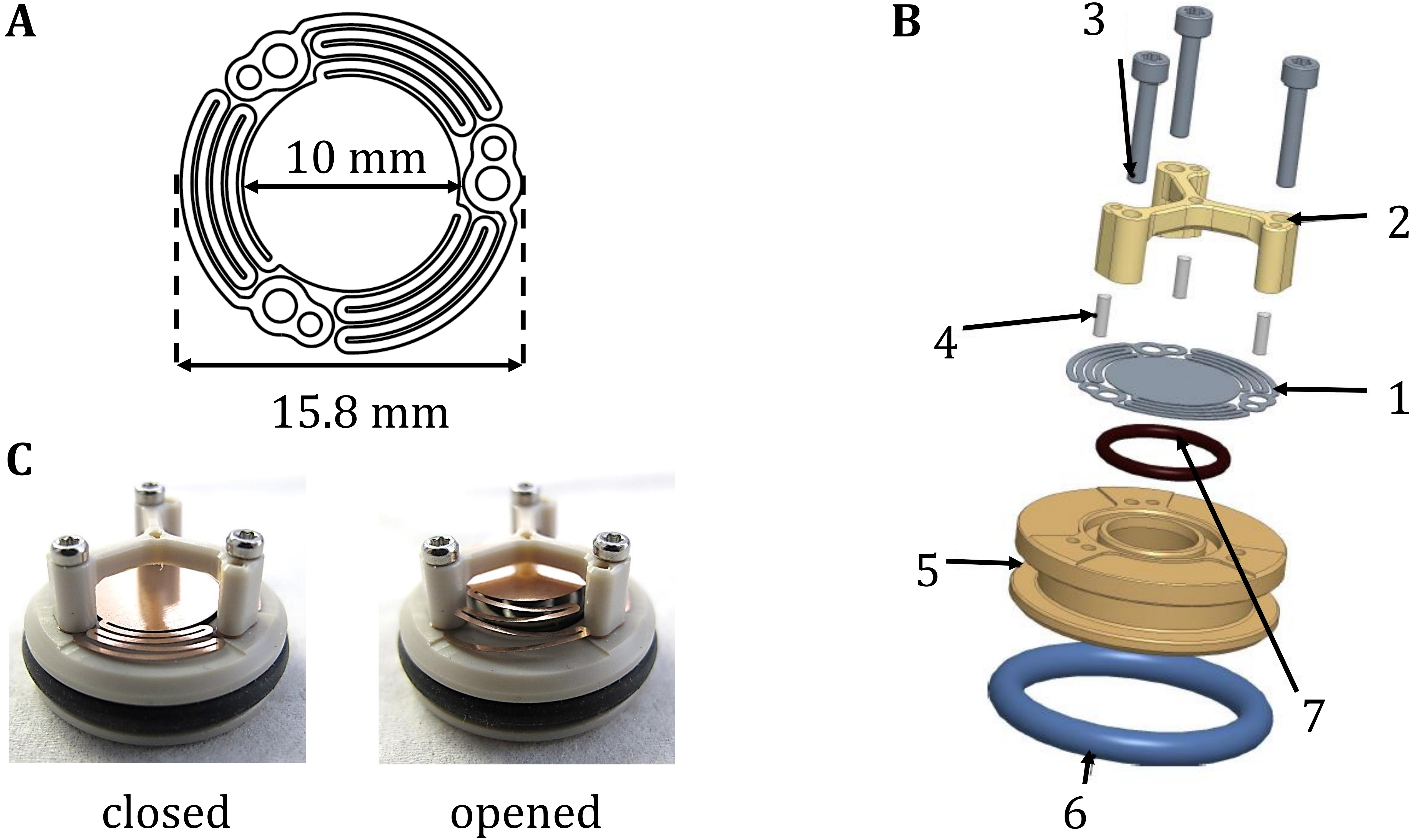
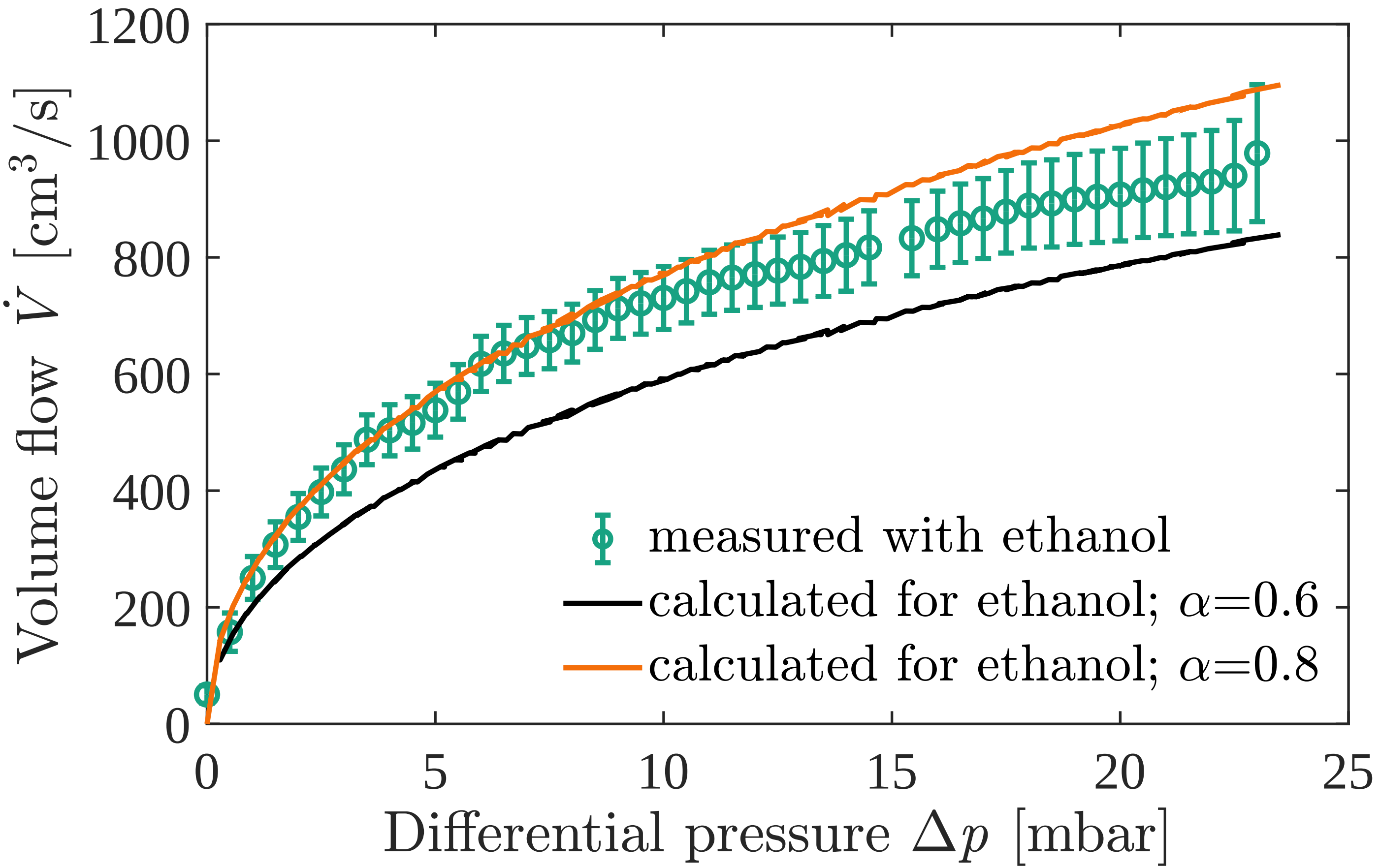
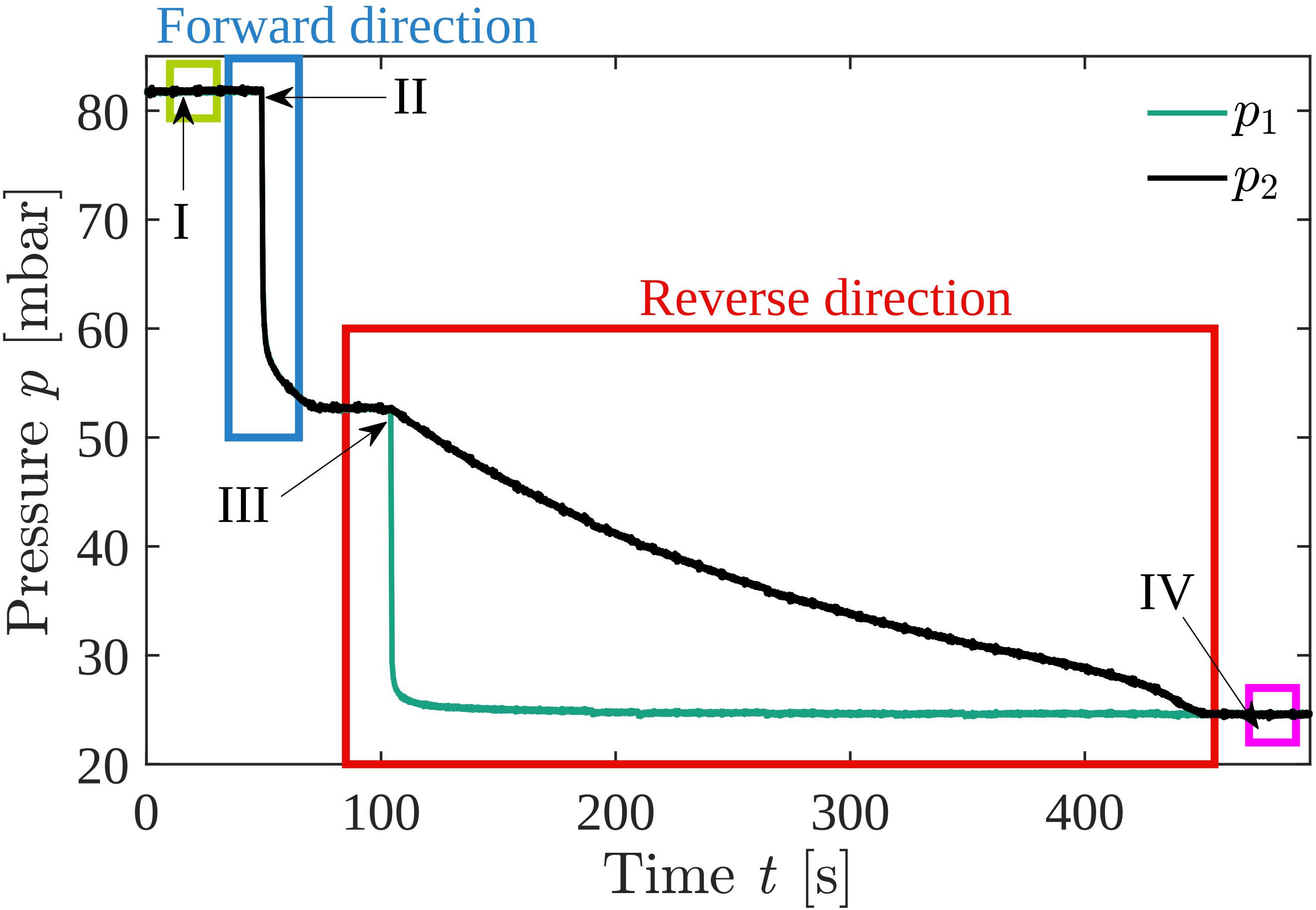

P1
P2
CV1
CV3
CV2
Check valve
Vapor and liquid
Reverse direction
R1
25 °C
R2
5 °C
R3
14 °C
Forward direction

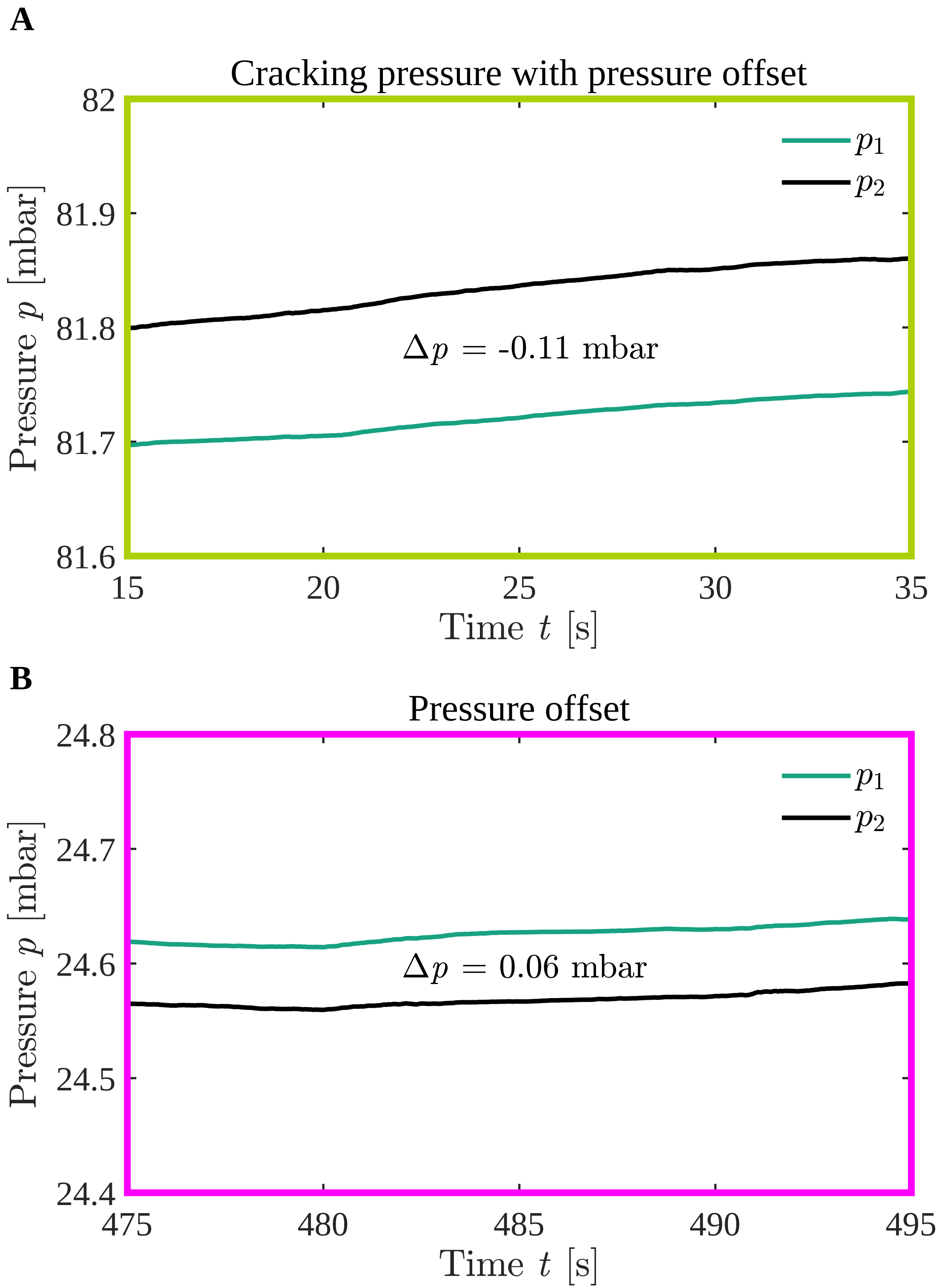

A
10 mm
15.8 mm
B
3
2
4
1
5
7
6
C
closed
opened

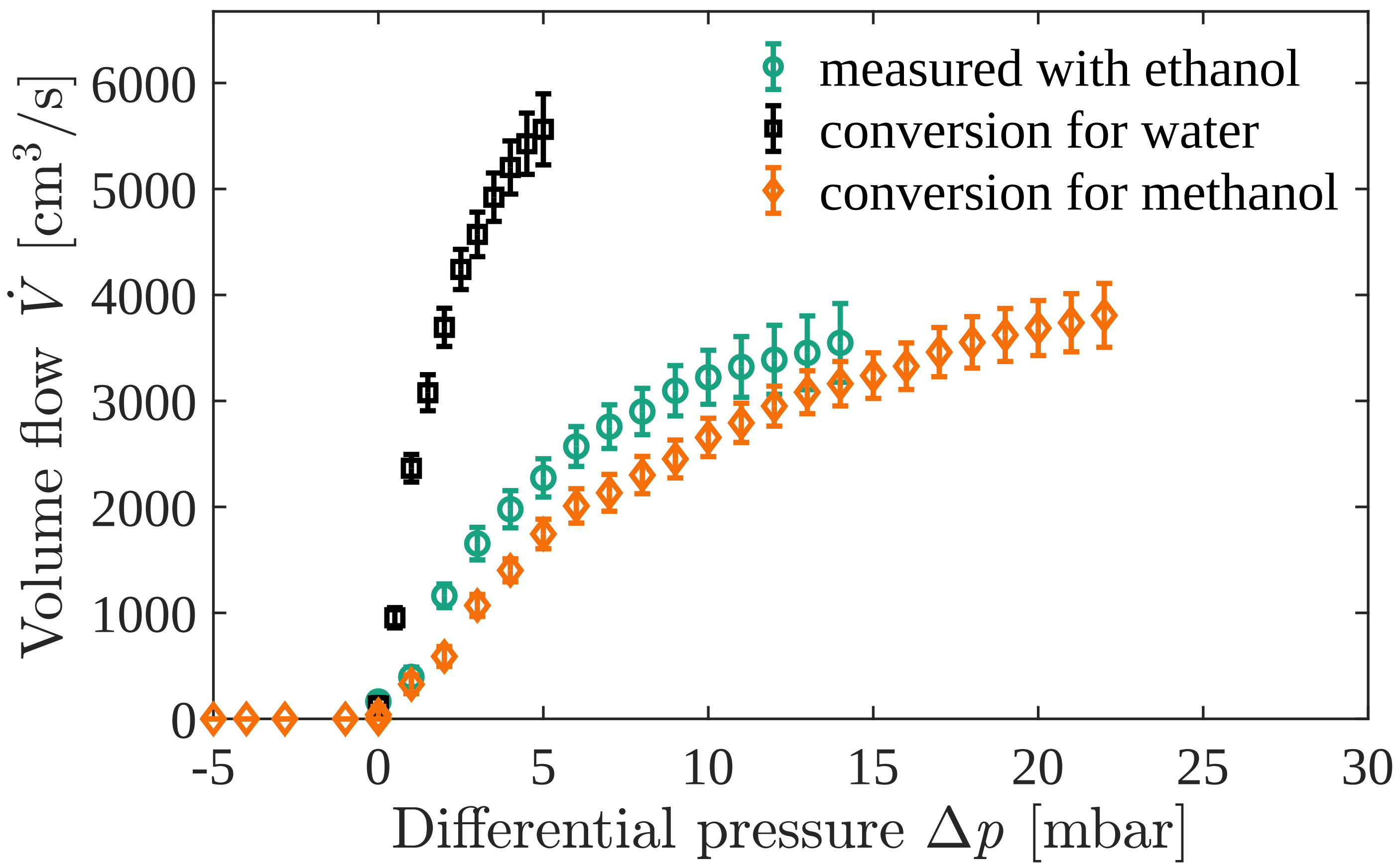


Volume flow $\dot{V}$ [cm^3/s]
Differential pressure Δp [mbar]
0
200
400
600
800
1000
1200
0
5
10
15
20
25
measured with ethanol
calculated for ethanol; α=0.6
calculated for ethanol; α=0.8

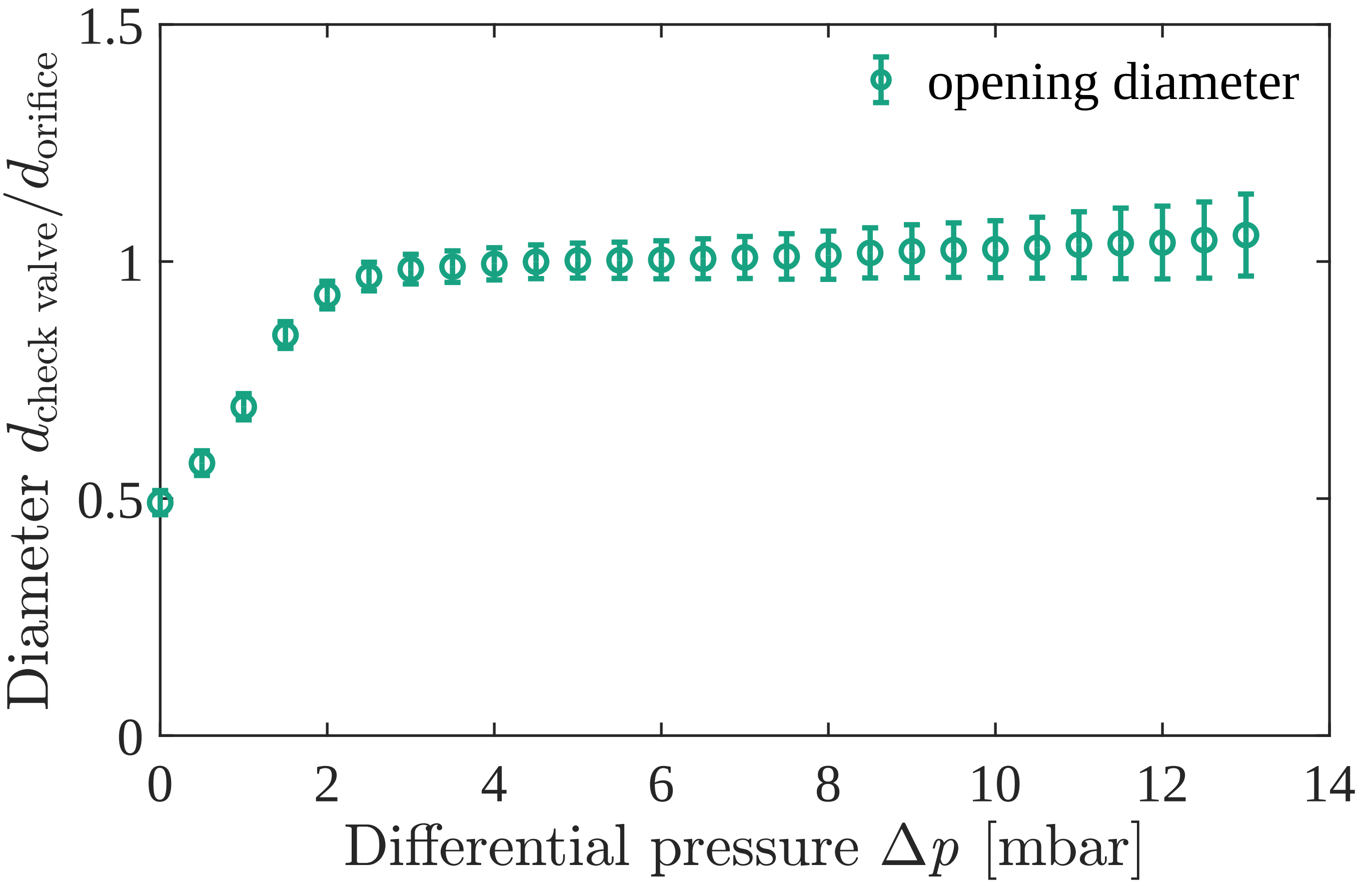


Forward direction
Reverse direction
I
II
III
IV
p_1
p_2
Pressure p [mbar]
Time t [s]
20
30
40
50
60
70
80
0
100
200
300
400

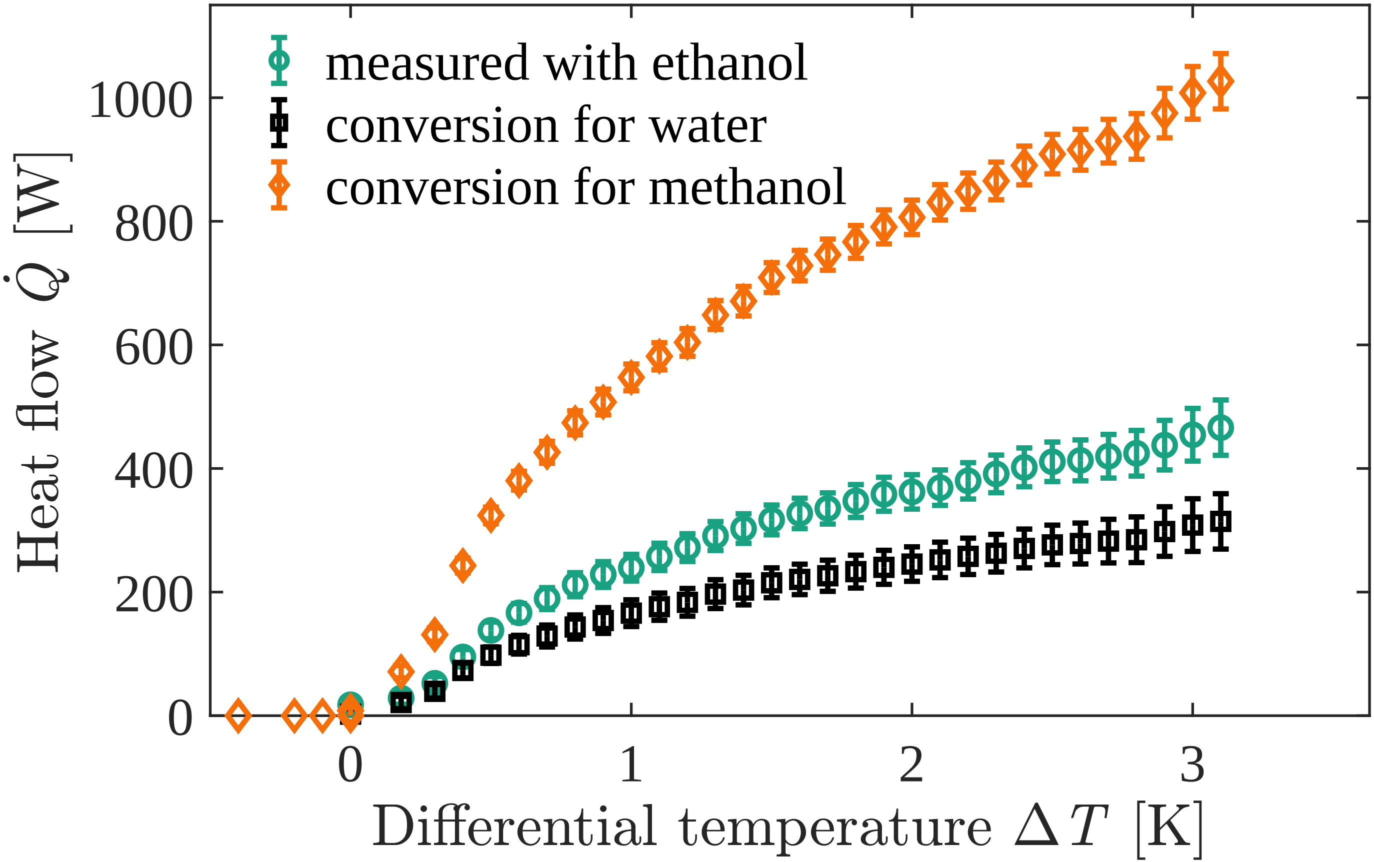

A
Cracking pressure with pressure offset
82
81.9
81.8
81.7
81.6
Pressure p [mbar]
p_1
p_2
Δp = -0.11 mbar
15
20
25
30
35
Time t [s]
B
Pressure offset
24.8
24.7
24.6
24.5
24.4
Pressure p [mbar]
p_1
p_2
Δp = 0.06 mbar
475
480
485
490
495
Time t [s]



measured with ethanol
conversion for water
conversion for methanol
Volume flow $\dot{V}$ [cm^3/s]
Differential pressure Δp [mbar]
0
1000
2000
3000
4000
5000
6000
-5
0
5
10
15
20
25
30



opening diameter
Diameter $d_{\text{check valve}}/d_{\text{orifice}}$
Differential pressure Δp [mbar]
0
0.5
1
1.5
0
2
4
6
8
10
12
14



measured with ethanol
conversion for water
conversion for methanol
Heat flow $\dot{Q}$ [W]
Differential temperature ΔT [K]
0
200
400
600
800
1000
0
1
2
3