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# Characterization of vacuum conductance in commercially available (sintered) and additively manufactured porous structures

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## ABSTRACT

This report documents the work performed in characterizing the vacuum conductance of porous structures made by conventional sintering (purchased as commercially available products from Mott Corporation ranging from 20 to 100 media grade) and additive manufacturing (powder bed fusion). The additively manufactured structures described in this report were originally intended to be the first iteration of several in an effort to produce desirable conductance characteristics. While resources were not available to link the experimental results to a modeling effort to better understand why certain characteristics were observed, the author hopes that this report may provide a useful set of data for future use, especially as sintered porous structures are not uncommonly procured from Mott corporation for research and development purposes. For that reason, all of the raw data is tabulated in the Appendix: it is possible to reproduce all of the figures shown in this report independently. For a quick order-of magnitude scan of the conductances, refer to Figures 5, 6, 8 and 9.

# ACKNOWLEDGEMENTS

Kyle LeBlanc provided guidance in the selection of the porous samples. Manuel A. Lopez Martinez provided valuable advice on the capabilities of the additive manufacturing machine and performed the fabrication of the samples.

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# 1. DESCRIPTION OF RELEVANT PARAMETERS, EXPERIMENTAL SYSTEM AND TESTED SAMPLES

## 1.1. Definition of conductance and throughput

Conductance is determined as the throughput divided by the pressure differential across the porous structure:

$$Conductance\ \left({}^{L}/_{sec}\right) = \frac{Throughput\ \left(torr * {}^{L}/_{sec}\right)}{\Delta P\ (torr)}$$

where throughput is analogous to mass flow rate ($\dot{m}$) for a given condition and is controlled by the mass flow controller.

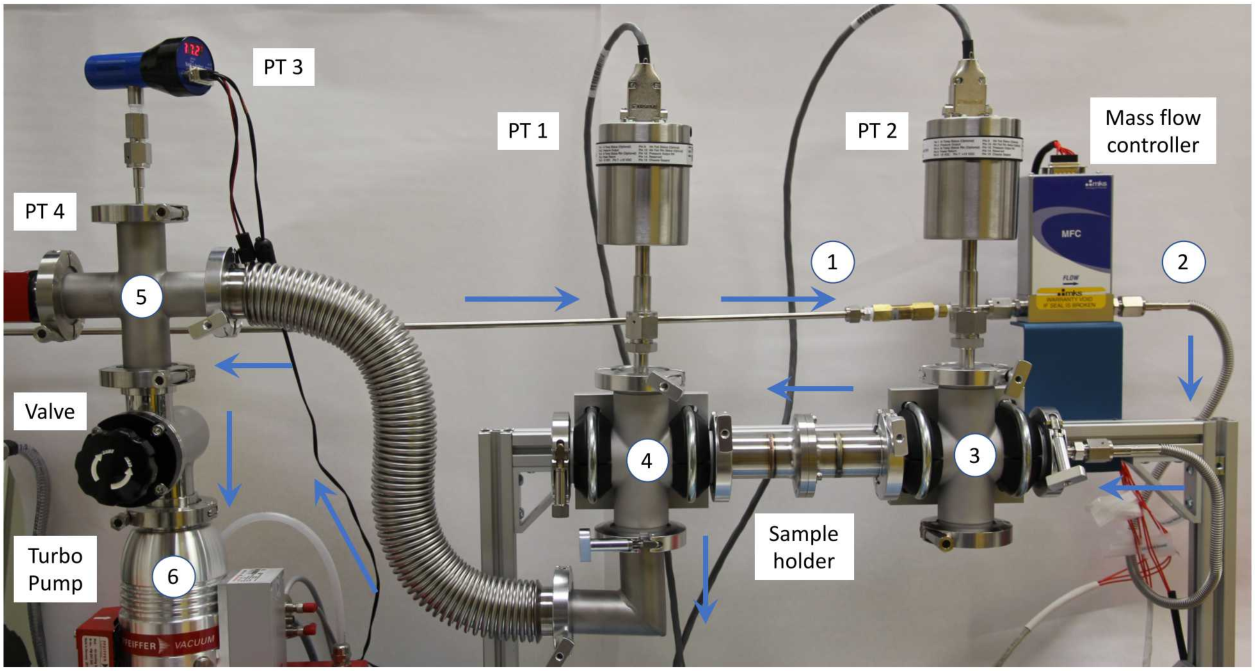
$$Throughput\ \left(torr * {}^{L}/_{sec}\right) = \frac{\dot{m}RT}{M}$$

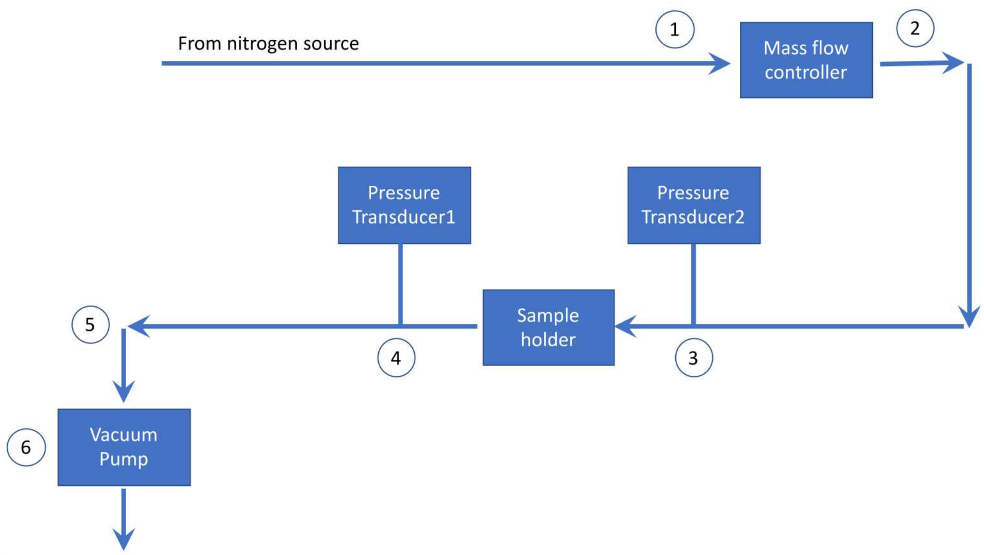
R, M, T are the universal gas constant, molar mass and temperature, respectively.

## 1.2. Experimental system

The experimental system used for the characterization is shown in Figure 1A below. Figure 1B schematically illustrates the primary components and gas flow direction. Nitrogen gas flows at a controlled rate from a source through a mass flow controller (1→2), through the porous sample (3→4) and through a vacuum pump (5→6). The pressures before and after the porous sample were measured by heated capacitance manometers (MKS 627F, 0-20 torr, MKS Instruments) with 0.2 mtorr accuracy in the pressure range measured (PT2 and PT1, respectively, in Figure 1A), and the nitrogen flow rate was controlled upstream with a thermal mass flow controller (MKS GE50A, 4-200 SCCM, MKS Instruments) with an accuracy of 1 SCCM, which was controlled with a program written in LabView. A turbomolecular pump (Hi-Cube 80, Pfeiffer Vacuum) was used to induce the flow. While additional pressure transducers (PT3 and PT4) are shown in Figure 1A, they were used only for experimental convenience and were not used to determine the conductance.

Figure 1C shows the porous sample holder. 1" diameter, 1/8" thick porous discs were used for all of the experiments. The sample holder was designed with two buna-N o-ring seals; while the first o-ring provided all of the necessary sealing against the porous disc as well as the atmosphere, a second o-ring was incorporated as a redundant seal against the atmosphere. In the sample holder, the available cross-sectional flow area across porous disc was reduced to a diameter of 0.8" (area= 3.24 $cm^2$).


PT 3
PT 1
PT 2
Mass flow
controller
PT 4
1
2
5
Valve
4
3
Sample
holder
Turbo
Pump
6
MFC
A)


From nitrogen source
1
Mass flow
controller
2
Pressure
Transducer1
Pressure
Transducer2
5
Sample
holder
4
3
6
Vacuum
Pump
B)

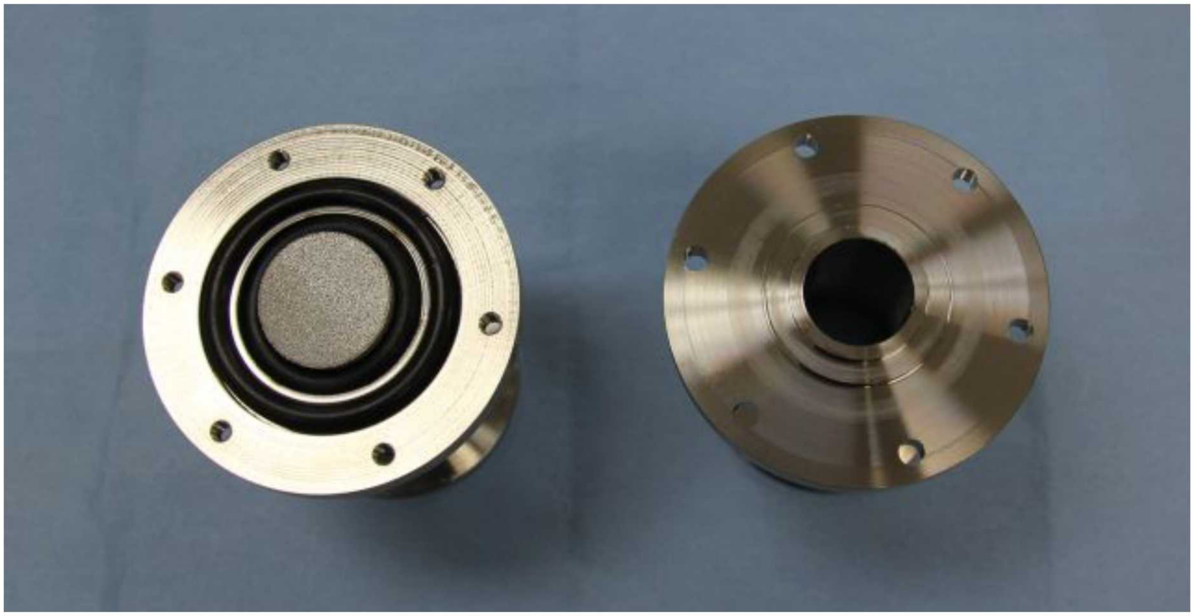
C) 

Figure 1.  A) shows the experimental system used to characterize the vacuum conductance of porous discs.  B) schematically shows the primary components shown in A as well as the gas flow.  The components in A and B are in the same locations and orientations.  C) Porous sample holder, showing the sealing mechanism with two concentric O-rings.

## 1.3.   Porous samples

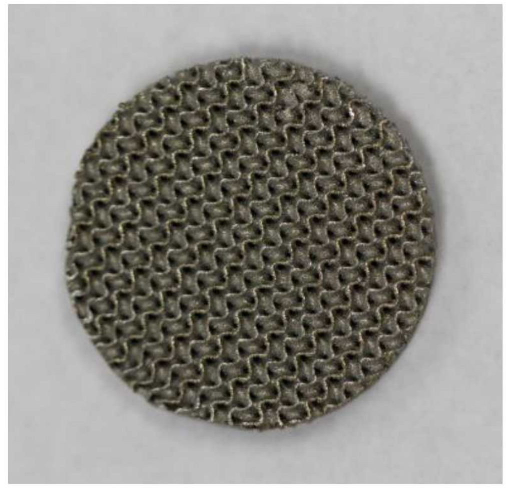
The porous samples characterized are shown in Figure 2 and 3.  Two types were tested: the first was a commercially available variety produced through low pressure sintering of non-spherical stainless steel powder (316L), purchased from Mott Corporation.  These samples came in different media grades, which were advised by Mott Corporation to correspond to effective pore size in micrometers.  20, 40, 80 and 100 media grade samples were characterized, where 80 media grade was a custom media size that was not normally available.  The second type was manufactured through powder bed fusion / additive manufacturing using 304L powder with a mean particle size of 40 um (3D Systems, ProX300).  The porous structures were fabricated as lattice structures using Gyroid and Schwartz D patterns designed an additive manufacturing software (3D Systems, 3DXpert). Figure 4 shows a screenshot of the software. Within the software, the Gyroid and Schwartz D patterns were customized by adjusting the X, Y, and Z dimensions of the representative cell and the thickness of the cell walls. All patterns were fabricated with a wall thickness of 0.1 mm; the X, Y and Z dimensions are indicated in millimeters as (X, Y, Z). As both manufacturing methods consist of some form of sintering, the methods will be referred as "sintered" and "additively manufactured" to avoid confusion.

A) 20 media grade B) 40 media grade

C) 80 media grade D) 100 media grade

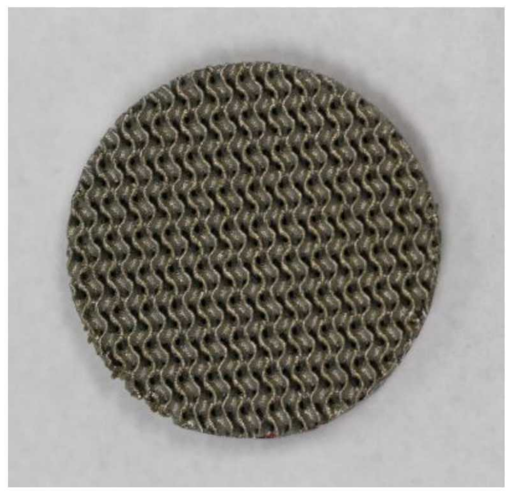
Figure 2. Porous discs manufactured through sintering (conventional powder metallurgy). Each sample is 1" in diameter.

Schwartz D, x=2.5, y=2, z=2

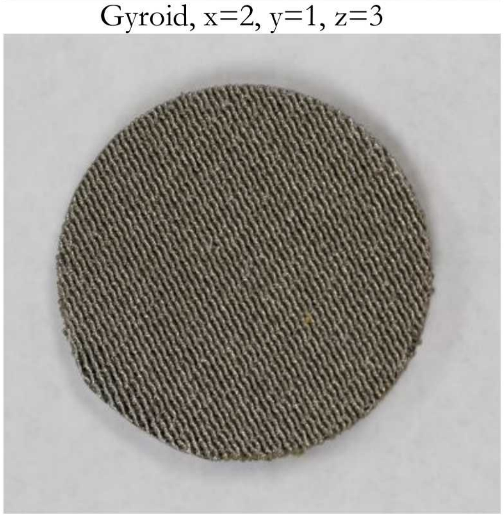


Gyroid, x=2.5, y=2, z=2

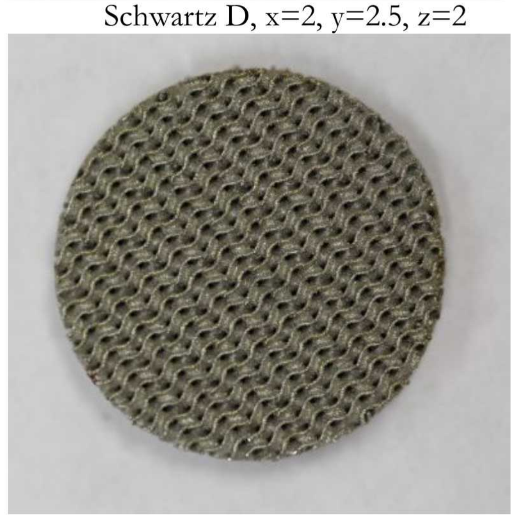
Gyroid, x=2, y=1, z=3



Schwartz D, x=2, y=2.5, z=2

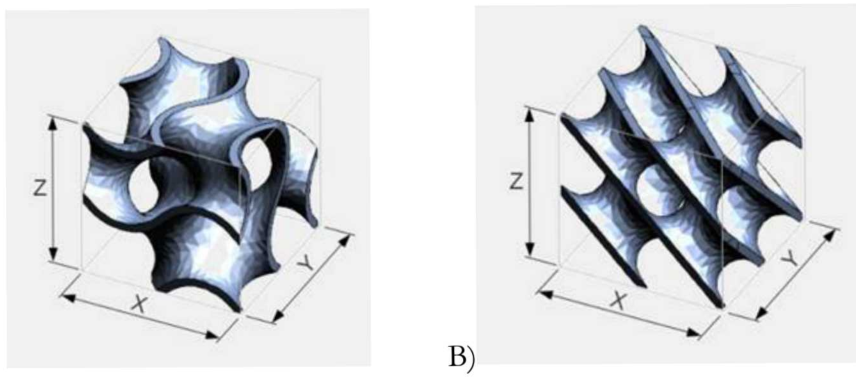


Schwartz D, x=2, y=1, z=3



Gyroid, x=2, y=2.5, z=2

Figure 3. Porous discs manufactured through additive manufacturing (powder bed fusion). Each sample is 1" in diameter.




A) B)

Figure 4. Schematic of (A) Gyroid and (B) Schwartz D unit cells and the parameters used to adjust their shape.

# 2. RESULTS

The experiments were performed by altering the metered nitrogen flow rate via the mass flow controller and recording the pressures upstream (high pressure) and downstream (low pressure, on the side of the vacuum pump) of the porous disc. The pressures were thus floating – both low and high side pressures were affected by the flow rate. This was due to the limited pumping capacity of the vacuum pump; if a vacuum pump with an infinite flow rate capacity was used, the low side pressure would have been pinned to approximately 0 torr. The capacity of the vacuum pump became noticeable at around 1 torr*L/s; the vacuum pump was not able to sustain a flow rate of 1.5 torr*L/s. Consequently, the highest flow rate tested was approximately 1.5 torr*L/s. The temperature of the gas and porous sample was 22-24 degrees C.

The effective pore size was used to calculate the Knudsen number, which was approximated by the media size for the sintered samples. The effective pore size of the additively manufactured samples were not able to be measured due to limitations in resources and hence Knudsen numbers were not calculated for these samples. Despite the gradual increase in low-side pressure with the increase in flow rate, the Knudsen number at the exit of the porous disc in all cases was in the regime of molecular flow (Kn>1). In contrast, the Knudsen number on the high-pressure side varied depending on the sample and flow rate, ranging from 0.1 to approximately 5. Consequently, for many of the conditions tested, a transition in flow regime occurred as the local pressure decreased across the porous sample. In general, the high-pressure side Knudsen number was smaller for lower flow rates, where the high side pressure was lower. For the remainder of his report, the high-pressure side Knudsen number will be used.

The data presented in the following figures are the average values of A) 5 samples tested for each media grade for the sintered samples, and B) available additively manufactured samples, shown as area-normalized values to eliminate geometry dependence. The standard deviation of the measured pressures and calculated conductances (not area-normalized) are shown in the Appendix. In general, the highest deviation (~10%) was seen in the lowest media grade for the sintered samples. This is likely due to the increased variability in packing at small particle sizes. Experimental repeatability in terms of conductance was observed to be approximately 3%, where the highest variance occurred at lower pressures. The lower repeatability of the manometer at such pressures (<0.01 torr at the low-pressure side) appeared to be the source of variance.

## 2.1. Sintered samples

Figures 5 and 6 show the throughput and conductance for the sintered samples. The throughput increases nearly linearly with the pressure differential across the porous sample for all cases where the high-pressure side (and approximately, pressure differentials) is above 1 torr, which is approximately where the flow transitions to molecular flow (Kn≈1). This transition point increases above 1 torr for lower media grade samples and decreases below 1 torr for higher media grade samples. This can be seen in the locations of the knee in Figure 6. Below the knee, the flow is mixed/molecular flow, and conductance drastically decreases. For reference, Figure 7 shows the relationship between conductance and the Knudsen number. Figure 7B suggests a linear relationship when in log-log form.

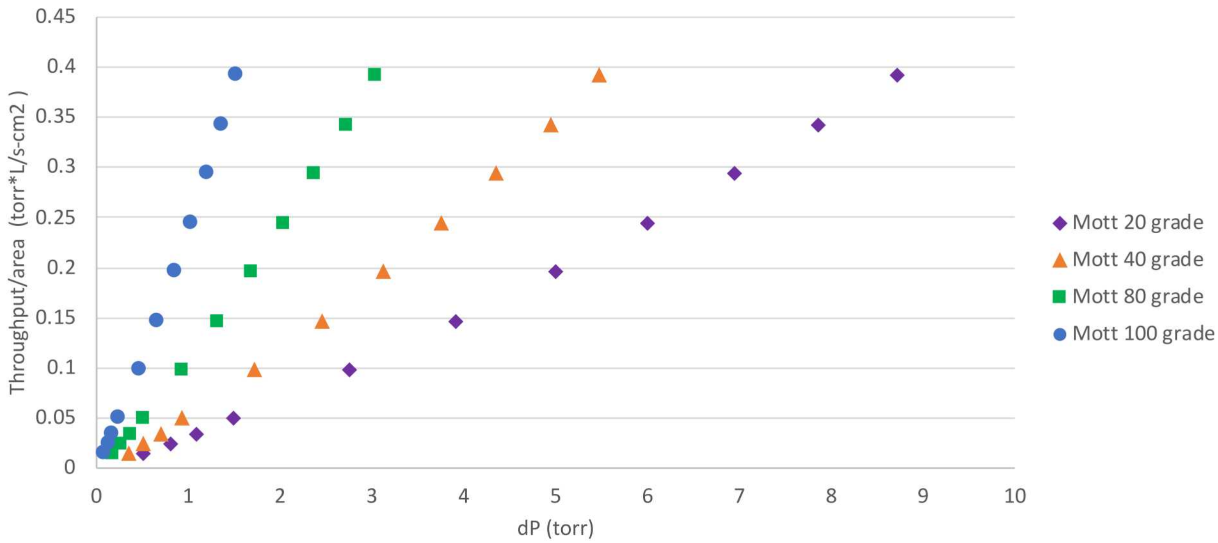



Figure 5. Throughput per unit area (proportional to mass flux) as a function of the pressure differential across the sintered discs.

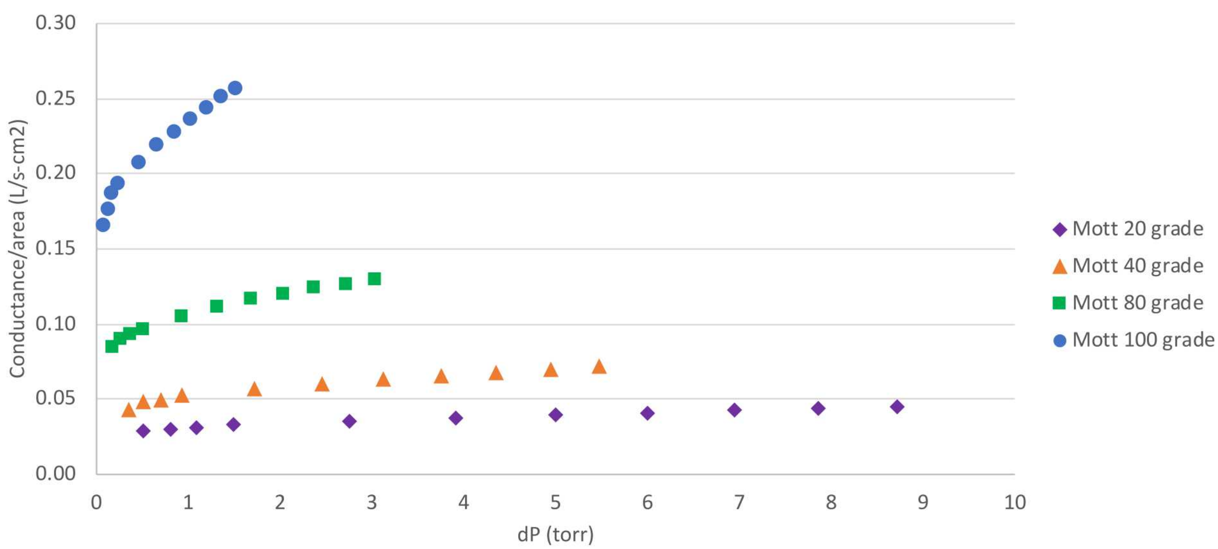
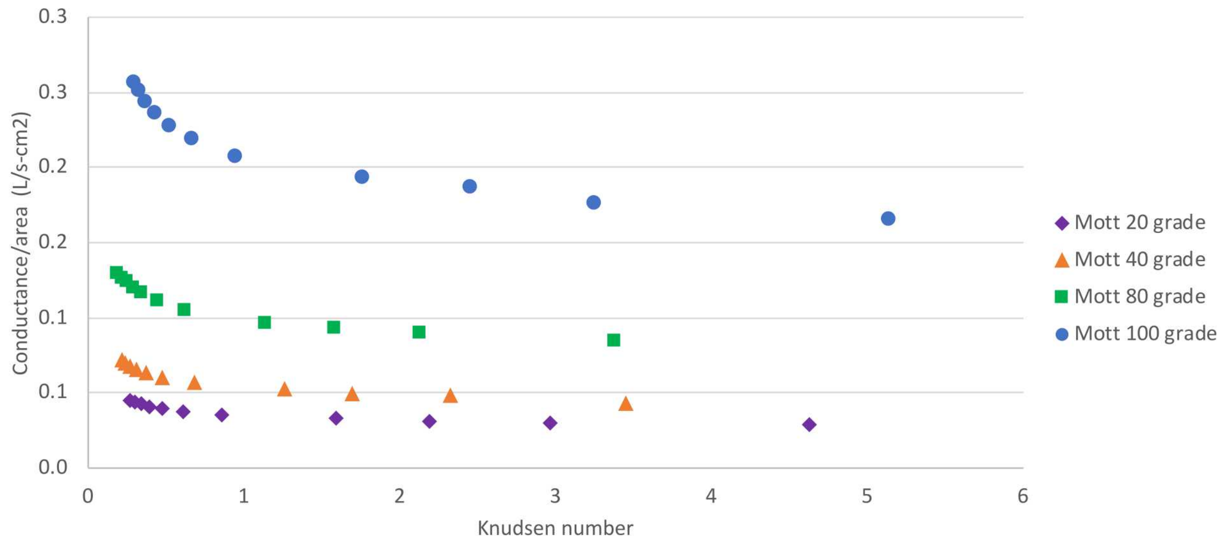
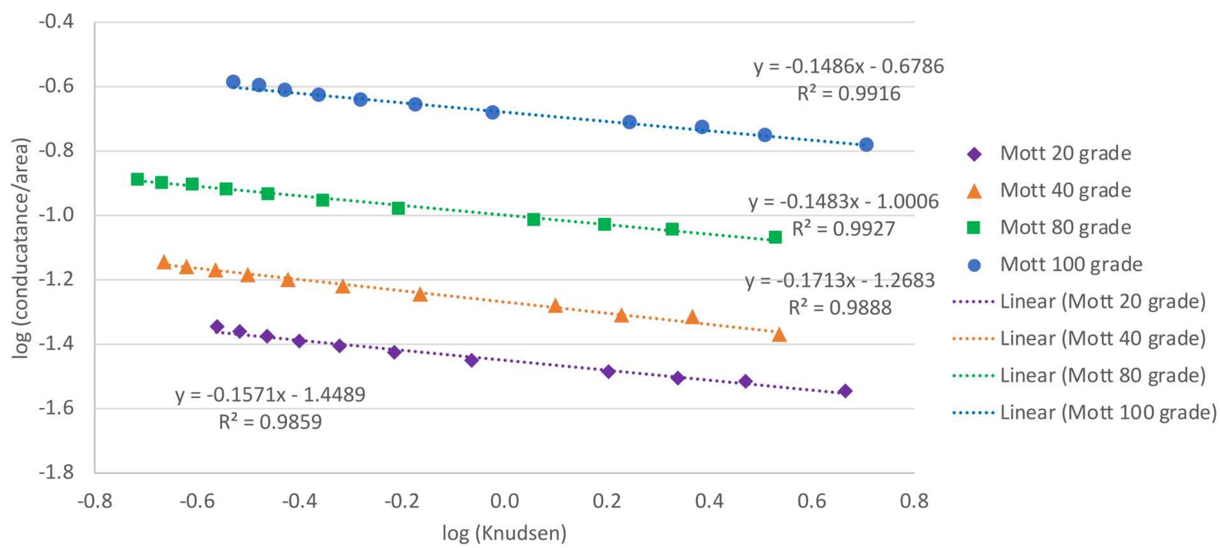



Figure 6. Conductance as a function of pressure differential across the sintered discs.




A)




B)

Figure 7. Conductance as a function of the Knudsen number. A) and B) show the same data, where B) presents it in log-log form.

## 2.2. Additively manufactured samples

Figures 8 and 9 show the throughput and conductance for the additively manufactured samples as a function of the pressure differential across the porous disc. The two figures can be compared to Figures 5 and 6 for the sintered analogue. For reference, Figures 10 and 11 show the data for both sintered and additively manufactured samples (Figures 5 & 8 and 6 & 9, respectively) for comparison. It is clear that the throughput and conductance are significantly higher than the sintered case; this is attributed most easily to the larger pore sizes that was apparent upon visual observation and secondarily and speculatively, the decrease in tortuosity in the sample. Due to the defined, repeated pattern in the additively manufactured samples, the effective travel length of gas across the sample is predetermined and equal throughout the sample. Significant lateral travel is likely not required for the gas to traverse across the sample, which may not necessarily be the case for the sintered samples.

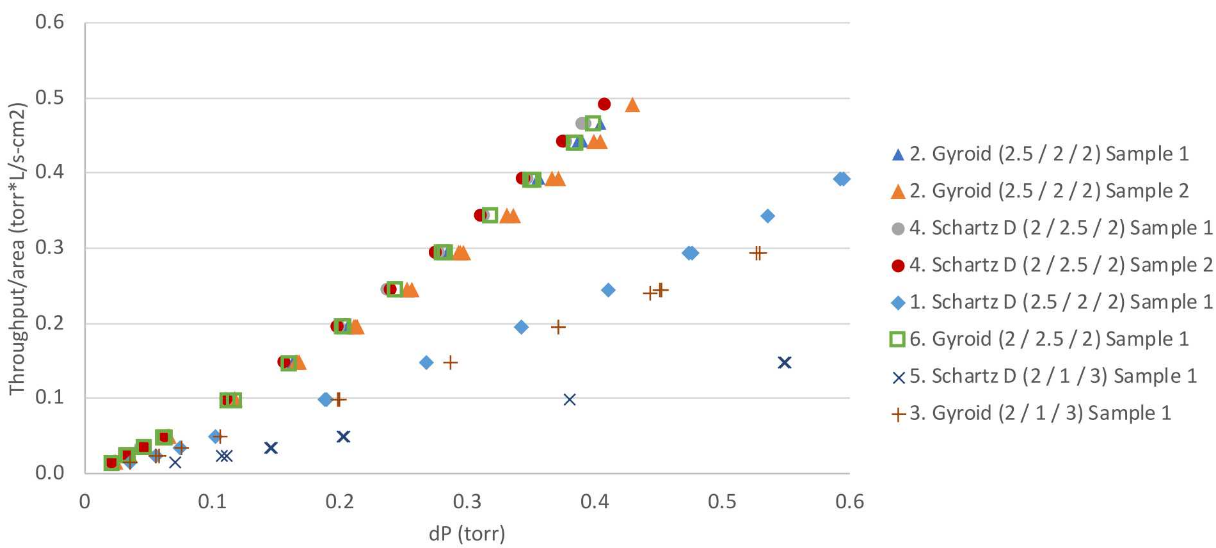



Figure 8. Throughput per unit area (proportional to mass flux) as a function of pressure differential across the additively manufactured discs. The values in the parenthesis refer to the X, Y and Z dimensions of the unit cell.

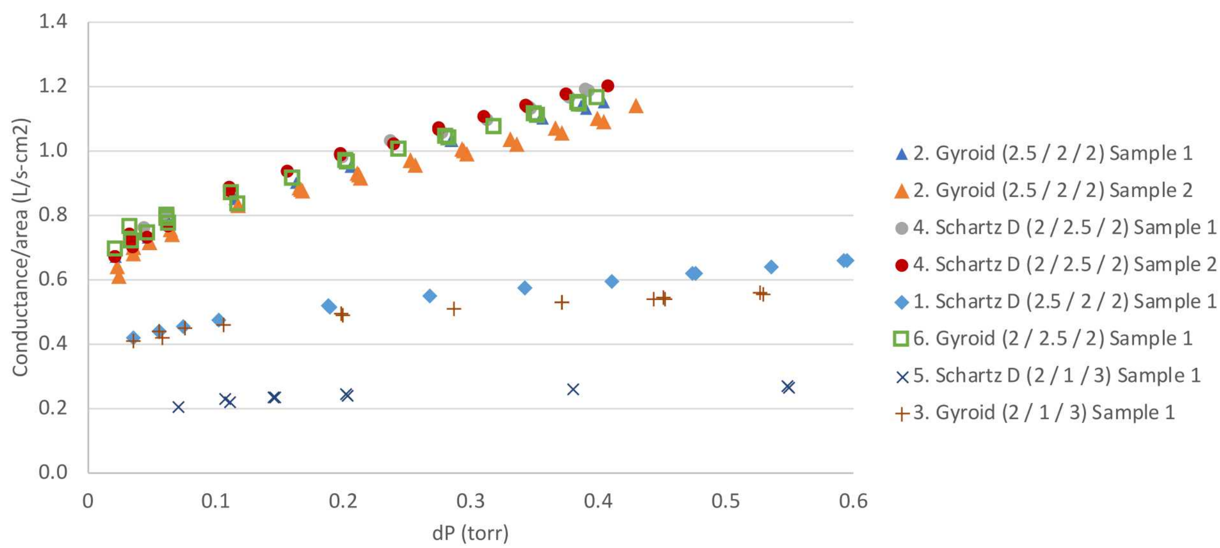



Figure 9. Conductance as a function of pressure differential across the additively manufactured discs. The values in the parenthesis refer to the X, Y and Z dimensions of the unit cell.

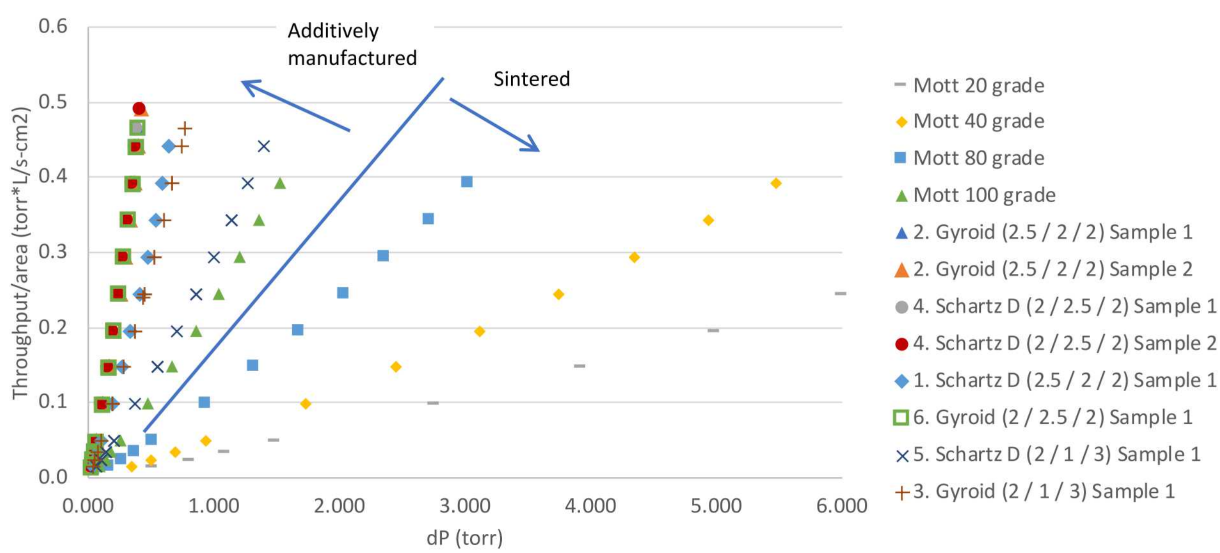



Figure 10. Throughput (mass flow rate) as a function of pressure differential across the porous samples. The values in the parenthesis refer to the X, Y and Z dimensions of the unit cell of the additively manufactured samples.

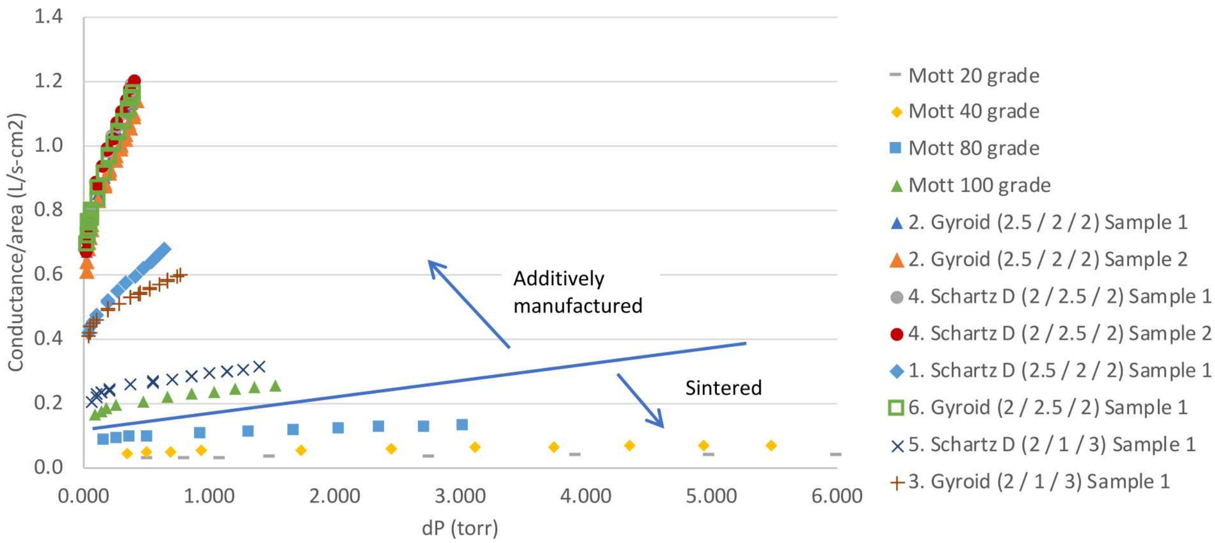



Figure 11. Conductance as a function of pressure differential across the porous samples. The values in the parenthesis refer to the X, Y and Z dimensions of the unit cell of the additively manufactured samples.

# APPENDIX A. DATA

Table 1: Data for sintered samples purchased from Mott Corporation. The data sets are labeled by the media grade size. The average conductance was calculated using the average dP at a given throughput. For reference, the individual conductances for the samples were calculated and averaged; the difference between the two methods of calculation were less 1%. The media grade (in micrometers) was used to calculate the Knudsen number.

Mott 20 media grade

| | SAMPLE 1 | | SAMPLE 2 | | SAMPLE 3 | | SAMPLE 4 | | SAMPLE 5 | |
|---|---|---|---|---|---|---|---|---|---|---|
| Throughput | P_low side | dP | P_low side | dP | P_low side | dP | P_low side | dP | P_low side | dP |
| (torr*L/s) | (torr) | (torr) | (torr) | (torr) | (torr) | (torr) | (torr) | (torr) | (torr) | (torr) |
| 0.048 | 0.004 | 0.489 | 0.007 | 0.449 | 0.004 | 0.504 | 0.004 | 0.566 | 0.004 | 0.582 |
| 0.079 | 0.009 | 0.742 | 0.011 | 0.745 | 0.009 | 0.757 | 0.009 | 0.879 | 0.009 | 0.906 |
| 0.111 | 0.013 | 1.006 | 0.014 | 1.025 | 0.013 | 1.018 | 0.012 | 1.187 | 0.013 | 1.223 |
| 0.159 | 0.018 | 1.389 | 0.019 | 1.425 | 0.018 | 1.394 | 0.017 | 1.637 | 0.018 | 1.618 |
| 0.318 | 0.031 | 2.578 | 0.031 | 2.675 | 0.03 | 2.578 | 0.03 | 3.026 | 0.031 | 2.954 |
| 0.477 | 0.041 | 3.666 | 0.041 | 3.805 | 0.04 | 3.662 | 0.04 | 4.29 | 0.041 | 4.18 |
| 0.635 | 0.050 | 4.676 | 0.049 | 4.851 | 0.049 | 4.667 | 0.049 | 5.459 | 0.05 | 5.315 |
| 0.794 | 0.059 | 5.624 | 0.058 | 5.825 | 0.058 | 5.615 | 0.057 | 6.552 | 0.059 | 6.375 |
| 0.953 | 0.067 | 6.524 | 0.066 | 6.746 | 0.067 | 6.51 | 0.066 | 7.583 | 0.068 | 7.376 |
| 1.112 | 0.077 | 7.38 | 0.075 | 7.621 | 0.077 | 7.362 | 0.075 | 8.561 | 0.078 | 8.323 |
| 1.271 | 0.087 | 8.199 | 0.085 | 8.456 | 0.088 | 8.176 | 0.086 | 9.494 | 0.091 | 9.226 |

| dP_avg | dP_std_dev | dP_std_dev % | Conduct_avg | cond_std_dev % | Knudsen_avg |
|---|---|---|---|---|---|
| (torr) | (torr) | (torr/torr) | (L/s) | [(L/s)/(L/s)] | non-dim |
| 0.518 | 0.055 | 10.7% | 0.092 | 10.81% | 4.63 |
| 0.806 | 0.080 | 9.9% | 0.099 | 9.63% | 2.97 |
| 1.092 | 0.104 | 9.6% | 0.102 | 9.28% | 2.19 |
| 1.493 | 0.124 | 8.3% | 0.106 | 8.13% | 1.60 |
| 2.762 | 0.213 | 7.7% | 0.115 | 7.58% | 0.86 |
| 3.921 | 0.295 | 7.5% | 0.122 | 7.40% | 0.61 |
| 4.994 | 0.370 | 7.4% | 0.127 | 7.28% | 0.48 |
| 5.998 | 0.437 | 7.3% | 0.132 | 7.16% | 0.40 |
| 6.948 | 0.500 | 7.2% | 0.137 | 7.06% | 0.34 |
| 7.849 | 0.557 | 7.1% | 0.142 | 6.96% | 0.30 |
| 8.710 | 0.611 | 7.0% | 0.146 | 6.88% | 0.27 |

Mott 40 media grade

| | SAMPLE 1 | | SAMPLE 2 | | SAMPLE 3 | | SAMPLE 4 | | SAMPLE 5 | |
|---|---|---|---|---|---|---|---|---|---|---|
| Throughput (torr*L/s) | P_low side (torr) | dP (torr) | P_low side (torr) | dP (torr) | P_low side (torr) | dP (torr) | P_low side (torr) | dP (torr) | P_low side (torr) | dP (torr) |
| 0.048 | | | 0.004 | 0.351 | 0.003 | 0.333 | 0.005 | 0.33 | 0.004 | 0.362 |
| 0.079 | 0.014 | 0.468 | 0.008 | 0.52 | 0.008 | 0.515 | 0.01 | 0.49 | 0.008 | 0.54 |
| 0.111 | | | 0.011 | 0.706 | 0.012 | 0.694 | 0.013 | 0.664 | 0.011 | 0.728 |
| 0.159 | 0.024 | 0.885 | 0.016 | 0.967 | 0.017 | 0.917 | 0.018 | 0.911 | 0.016 | 0.998 |
| 0.318 | 0.038 | 1.66 | 0.029 | 1.784 | 0.031 | 1.673 | 0.03 | 1.679 | 0.029 | 1.848 |
| 0.477 | 0.050 | 2.371 | 0.039 | 2.524 | 0.041 | 2.372 | 0.04 | 2.379 | 0.039 | 2.62 |
| 0.635 | 0.061 | 3.029 | 0.049 | 3.207 | 0.05 | 3.021 | 0.049 | 3.028 | 0.048 | 3.333 |
| 0.794 | 0.070 | 3.647 | 0.057 | 3.846 | 0.059 | 3.629 | 0.057 | 3.636 | 0.056 | 4.001 |
| 0.953 | 0.081 | 4.229 | 0.067 | 4.449 | 0.068 | 4.202 | 0.066 | 4.21 | 0.065 | 4.632 |
| 1.112 | | | 0.078 | 5.021 | 0.078 | 4.748 | 0.075 | 4.756 | 0.075 | 5.23 |
| 1.271 | | | 0.089 | 5.566 | 0.09 | 5.27 | 0.085 | 5.279 | 0.085 | 5.801 |

| dP_avg (torr) | dP_std_dev (torr) | dP_std_dev % (torr/torr) | Conduct_avg (L/s) | cond_std_dev % [(L/s)/(L/s)] | Knudsen_avg non-dim |
|---|---|---|---|---|---|
| 0.344 | 0.015 | 4.4% | 0.139 | 4.38% | 3.45 |
| 0.507 | 0.028 | 5.5% | 0.157 | 5.63% | 2.33 |
| 0.698 | 0.027 | 3.8% | 0.159 | 3.86% | 1.69 |
| 0.936 | 0.046 | 4.9% | 0.170 | 4.84% | 1.26 |
| 1.729 | 0.083 | 4.8% | 0.184 | 4.69% | 0.68 |
| 2.453 | 0.114 | 4.6% | 0.194 | 4.52% | 0.48 |
| 3.124 | 0.141 | 4.5% | 0.203 | 4.40% | 0.38 |
| 3.752 | 0.166 | 4.4% | 0.212 | 4.32% | 0.32 |
| 4.344 | 0.191 | 4.4% | 0.219 | 4.27% | 0.27 |
| 4.939 | 0.232 | 4.7% | 0.225 | 4.64% | 0.24 |
| 5.479 | 0.255 | 4.7% | 0.232 | 4.59% | 0.22 |

Mott 80 media grade

| | SAMPLE 1 | | SAMPLE 2 | | SAMPLE 3 | | SAMPLE 4 | | SAMPLE 5 | |
|---|---|---|---|---|---|---|---|---|---|---|
| Throughput (torr*L/s) | P_low side (torr) | dP (torr) | P_low side (torr) | dP (torr) | P_low side (torr) | dP (torr) | P_low side (torr) | dP (torr) | P_low side (torr) | dP (torr) |
| 0.048 | 0.009 | 0.156 | 0.004 | 0.175 | 0.004 | 0.169 | 0.003 | 0.187 | 0.004 | 0.178 |
| 0.079 | 0.012 | 0.245 | 0.008 | 0.272 | 0.009 | 0.274 | 0.009 | 0.293 | 0.009 | 0.28 |
| 0.111 | 0.017 | 0.333 | 0.012 | 0.353 | 0.012 | 0.377 | 0.011 | 0.4 | 0.013 | 0.379 |
| 0.159 | 0.021 | 0.46 | 0.016 | 0.484 | 0.018 | 0.524 | 0.016 | 0.554 | 0.018 | 0.523 |
| 0.318 | 0.034 | 0.861 | 0.029 | 0.894 | 0.03 | 0.939 | 0.029 | 1.035 | 0.03 | 0.937 |
| 0.477 | 0.043 | 1.231 | 0.039 | 1.272 | 0.04 | 1.345 | 0.038 | 1.422 | 0.04 | 1.327 |
| 0.635 | 0.051 | 1.579 | 0.048 | 1.627 | 0.048 | 1.721 | 0.047 | 1.803 | 0.048 | 1.699 |
| 0.794 | 0.059 | 1.908 | 0.057 | 1.962 | 0.057 | 2.076 | 0.055 | 2.181 | 0.057 | 2.05 |
| 0.953 | 0.070 | 2.222 | 0.065 | 2.28 | 0.065 | 2.413 | 0.064 | 2.534 | 0.066 | 2.383 |
| 1.112 | | | 0.076 | 2.583 | 0.074 | 2.733 | 0.073 | 2.871 | 0.075 | 2.704 |
| 1.271 | | | 0.09 | 2.871 | 0.085 | 3.039 | 0.083 | 3.194 | 0.086 | 3.004 |

| dP_avg (torr) | dP_std_dev (torr) | dP_std_dev % (torr/torr) | Conduct_avg (L/s) | cond_std_dev % [(L/s)/(L/s)] | Knudsen_avg non-dim |
|---|---|---|---|---|---|
| 0.173 | 0.012 | 6.7% | 0.275 | 6.87% | 3.38 |
| 0.273 | 0.018 | 6.4% | 0.291 | 6.76% | 2.13 |
| 0.368 | 0.026 | 7.0% | 0.302 | 7.19% | 1.58 |
| 0.509 | 0.037 | 7.3% | 0.312 | 7.43% | 1.14 |
| 0.933 | 0.065 | 7.0% | 0.340 | 6.82% | 0.62 |
| 1.319 | 0.073 | 5.5% | 0.361 | 5.50% | 0.44 |
| 1.686 | 0.087 | 5.1% | 0.377 | 5.14% | 0.35 |
| 2.035 | 0.106 | 5.2% | 0.390 | 5.18% | 0.29 |
| 2.366 | 0.121 | 5.1% | 0.403 | 5.11% | 0.25 |
| 2.723 | 0.118 | 4.3% | 0.408 | 4.34% | 0.21 |
| 3.027 | 0.133 | 4.4% | 0.420 | 4.38% | 0.19 |

Mott 100 media grade

| Throughput (torr*L/s) | SAMPLE 1 P_low side (torr) | SAMPLE 1 dP (torr) | SAMPLE 2 P_low side (torr) | SAMPLE 2 dP (torr) | SAMPLE 3 P_low side (torr) | SAMPLE 3 dP (torr) | SAMPLE 4 P_low side (torr) | SAMPLE 4 dP (torr) | SAMPLE 5 P_low side (torr) | SAMPLE 5 dP (torr) |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.048 | 0.009 | 0.088 | 0.003 | 0.087 | 0.003 | 0.089 | 0.003 | 0.092 | 0.003 | 0.09 |
| 0.079 | 0.013 | 0.138 | 0.007 | 0.135 | 0.007 | 0.14 | 0.007 | 0.143 | 0.008 | 0.14 |
| 0.111 | 0.017 | 0.186 | 0.011 | 0.182 | 0.01 | 0.184 | 0.01 | 0.186 | 0.011 | 0.181 |
| 0.159 | 0.021 | 0.257 | 0.016 | 0.251 | 0.015 | 0.253 | 0.015 | 0.259 | 0.016 | 0.251 |
| 0.318 | 0.033 | 0.478 | 0.029 | 0.469 | 0.027 | 0.47 | 0.027 | 0.483 | 0.029 | 0.467 |
| 0.477 | 0.044 | 0.687 | 0.038 | 0.646 | 0.037 | 0.673 | 0.037 | 0.692 | 0.039 | 0.667 |
| 0.635 | 0.052 | 0.879 | 0.047 | 0.822 | 0.046 | 0.864 | 0.046 | 0.888 | 0.048 | 0.856 |
| 0.794 | 0.063 | 1.062 | 0.055 | 0.993 | 0.055 | 1.042 | 0.055 | 1.073 | 0.057 | 1.034 |
| 0.953 | 0.074 | 1.232 | 0.064 | 1.156 | 0.063 | 1.213 | 0.064 | 1.249 | 0.065 | 1.204 |
| 1.112 | | | 0.072 | 1.313 | 0.071 | 1.377 | 0.073 | 1.417 | 0.074 | 1.365 |
| 1.271 | 0.095 | 1.556 | 0.082 | 1.463 | 0.081 | 1.533 | 0.082 | 1.579 | 0.084 | 1.52 |

| dP_avg (torr) | dP_std_dev (torr) | dP_std_dev % (torr/torr) | Conduct_avg (L/s) | cond_std_dev % [(L/s)/(L/s)] | Knudsen_avg non-dim |
|---|---|---|---|---|---|
| 0.089 | 0.002 | 2.2% | 0.534 | 2.14% | 5.14 |
| 0.139 | 0.003 | 2.1% | 0.571 | 2.13% | 3.25 |
| 0.184 | 0.002 | 1.2% | 0.605 | 1.24% | 2.46 |
| 0.254 | 0.004 | 1.4% | 0.625 | 1.42% | 1.77 |
| 0.473 | 0.007 | 1.4% | 0.671 | 1.43% | 0.96 |
| 0.673 | 0.018 | 2.7% | 0.708 | 2.74% | 0.67 |
| 0.862 | 0.026 | 3.0% | 0.737 | 3.02% | 0.53 |
| 1.041 | 0.031 | 3.0% | 0.763 | 3.02% | 0.44 |
| 1.211 | 0.035 | 2.9% | 0.787 | 2.96% | 0.38 |
| 1.368 | 0.043 | 3.1% | 0.813 | 3.16% | 0.33 |
| 1.530 | 0.044 | 2.9% | 0.831 | 2.91% | 0.30 |

Table 2: Data for additively manufactured samples. The data is labeled as SAMPLE TYPE (UNIT CELL X-DIM, Y-DIM, Z-DIM) SAMPLE NUMBER.

Gyroid (2.5 / 2 / 2) Sample 1

| P_low (torr) | P_High (torr) | dP (torr) | Throughput (torr*L/s) | Conductance (L/s) |
|---|---|---|---|---|
| 0.069 | 0.354 | 0.285 | 0.953 | 3.344 |
| 0.087 | 0.443 | 0.356 | 1.271 | 3.570 |
| 0.097 | 0.487 | 0.39 | 1.430 | 3.666 |
| 0.072 | 0.357 | 0.285 | 0.953 | 3.344 |
| 0.092 | 0.447 | 0.355 | 1.271 | 3.580 |
| 0.106 | 0.493 | 0.387 | 1.430 | 3.694 |
| 0.054 | 0.26 | 0.206 | 0.635 | 3.085 |
| 0.044 | 0.207 | 0.163 | 0.477 | 2.924 |
| 0.034 | 0.149 | 0.115 | 0.318 | 2.763 |
| 0.022 | 0.085 | 0.063 | 0.159 | 2.522 |
| 0.017 | 0.064 | 0.047 | 0.111 | 2.366 |
| 0.013 | 0.048 | 0.035 | 0.079 | 2.269 |
| 0.01 | 0.032 | 0.022 | 0.048 | 2.166 |
| 0.034 | 0.149 | 0.115 | 0.318 | 2.763 |
| 0.053 | 0.259 | 0.206 | 0.635 | 3.085 |
| 0.069 | 0.355 | 0.286 | 0.953 | 3.333 |
| 0.086 | 0.443 | 0.357 | 1.271 | 3.560 |
| 0.107 | 0.511 | 0.404 | 1.509 | 3.736 |

Gyroid (2.5 / 2 / 2) Sample 2

| P_low (torr) | P_High (torr) | dP (torr) | Throughput (torr*L/s) | Conductance (L/s) |
|---|---|---|---|---|
| 0.005 | 0.029 | 0.024 | 0.048 | 1.986 |
| 0.01 | 0.045 | 0.035 | 0.079 | 2.269 |
| 0.013 | 0.061 | 0.048 | 0.111 | 2.317 |
| 0.018 | 0.083 | 0.065 | 0.159 | 2.444 |
| 0.031 | 0.149 | 0.118 | 0.318 | 2.693 |
| 0.041 | 0.208 | 0.167 | 0.477 | 2.854 |
| 0.05 | 0.261 | 0.211 | 0.635 | 3.012 |
| 0.058 | 0.311 | 0.253 | 0.794 | 3.140 |
| 0.066 | 0.36 | 0.294 | 0.953 | 3.242 |
| 0.075 | 0.406 | 0.331 | 1.112 | 3.360 |
| 0.084 | 0.45 | 0.366 | 1.271 | 3.472 |
| 0.068 | 0.361 | 0.293 | 0.953 | 3.253 |
| 0.051 | 0.263 | 0.212 | 0.635 | 2.997 |
| 0.032 | 0.15 | 0.118 | 0.318 | 2.693 |
| 0.012 | 0.047 | 0.035 | 0.079 | 2.269 |
| 0.02 | 0.086 | 0.066 | 0.159 | 2.407 |
| 0.042 | 0.208 | 0.166 | 0.477 | 2.871 |
| 0.059 | 0.312 | 0.253 | 0.794 | 3.140 |
| 0.074 | 0.405 | 0.331 | 1.112 | 3.360 |
| 0.093 | 0.493 | 0.4 | 1.430 | 3.574 |
| 0.109 | 0.539 | 0.43 | 1.589 | 3.694 |
| 0.005 | 0.028 | 0.023 | 0.048 | 2.072 |
| 0.009 | 0.045 | 0.036 | 0.079 | 2.206 |
| 0.012 | 0.06 | 0.048 | 0.111 | 2.317 |
| 0.017 | 0.083 | 0.066 | 0.159 | 2.407 |
| 0.029 | 0.147 | 0.118 | 0.318 | 2.693 |
| 0.039 | 0.207 | 0.168 | 0.477 | 2.837 |
| 0.048 | 0.262 | 0.214 | 0.635 | 2.969 |
| 0.056 | 0.313 | 0.257 | 0.794 | 3.091 |
| 0.065 | 0.362 | 0.297 | 0.953 | 3.209 |
| 0.073 | 0.409 | 0.336 | 1.112 | 3.310 |
| 0.083 | 0.454 | 0.371 | 1.271 | 3.426 |
| 0.094 | 0.498 | 0.404 | 1.430 | 3.539 |

Schartz D (2 / 2.5 / 2) Sample 1

| P_low (torr) | P_High (torr) | dP (torr) | Throughput (torr*L/s) | Conductance (L/s) |
|---|---|---|---|---|
| 0.005 | 0.027 | 0.022 | 0.048 | 2.166 |
| 0.009 | 0.043 | 0.034 | 0.079 | 2.336 |
| 0.013 | 0.058 | 0.045 | 0.111 | 2.471 |
| 0.018 | 0.079 | 0.061 | 0.159 | 2.604 |
| 0.03 | 0.141 | 0.111 | 0.318 | 2.862 |
| 0.04 | 0.197 | 0.157 | 0.477 | 3.036 |
| 0.049 | 0.249 | 0.2 | 0.635 | 3.177 |
| 0.059 | 0.297 | 0.238 | 0.794 | 3.337 |
| 0.065 | 0.343 | 0.278 | 0.953 | 3.429 |
| 0.074 | 0.387 | 0.313 | 1.112 | 3.553 |
| 0.084 | 0.43 | 0.346 | 1.271 | 3.673 |
| 0.095 | 0.472 | 0.377 | 1.430 | 3.792 |
| 0.107 | 0.498 | 0.391 | 1.509 | 3.860 |
| 0.07 | 0.346 | 0.276 | 0.953 | 3.454 |
| 0.052 | 0.252 | 0.2 | 0.635 | 3.177 |
| 0.033 | 0.144 | 0.111 | 0.318 | 2.862 |
| 0.02 | 0.081 | 0.061 | 0.159 | 2.604 |
| 0.083 | 0.43 | 0.347 | 1.271 | 3.663 |
| 0.094 | 0.472 | 0.378 | 1.430 | 3.782 |
| 0.101 | 0.494 | 0.393 | 1.509 | 3.840 |

Schartz D (2 / 2.5 / 2) Sample 2

| P_low (torr) | P_High (torr) | dP (torr) | Throughput (torr*L/s) | Conductance (L/s) |
|---|---|---|---|---|
| 0.005 | 0.027 | 0.022 | 0.048 | 2.166 |
| 0.009 | 0.044 | 0.035 | 0.079 | 2.269 |
| 0.013 | 0.06 | 0.047 | 0.111 | 2.366 |
| 0.019 | 0.083 | 0.064 | 0.159 | 2.482 |
| 0.031 | 0.143 | 0.112 | 0.318 | 2.837 |
| 0.041 | 0.198 | 0.157 | 0.477 | 3.036 |
| 0.05 | 0.249 | 0.199 | 0.635 | 3.193 |
| 0.058 | 0.298 | 0.24 | 0.794 | 3.310 |
| 0.067 | 0.343 | 0.276 | 0.953 | 3.454 |
| 0.076 | 0.387 | 0.311 | 1.112 | 3.576 |
| 0.086 | 0.431 | 0.345 | 1.271 | 3.684 |
| 0.098 | 0.473 | 0.375 | 1.430 | 3.813 |
| 0.087 | 0.431 | 0.344 | 1.271 | 3.694 |
| 0.07 | 0.345 | 0.275 | 0.953 | 3.466 |
| 0.052 | 0.25 | 0.198 | 0.635 | 3.209 |
| 0.033 | 0.144 | 0.111 | 0.318 | 2.862 |
| 0.013 | 0.046 | 0.033 | 0.079 | 2.407 |
| 0.009 | 0.031 | 0.022 | 0.048 | 2.166 |
| 0.013 | 0.047 | 0.034 | 0.079 | 2.336 |
| 0.1 | 0.508 | 0.408 | 1.589 | 3.894 |

Gyroid (2 / 2.5 / 2) Sample 1

| P_low (torr) | P_High (torr) | dP (torr) | Throughput (torr*L/s) | Conductance (L/s) |
|---|---|---|---|---|
| 0.004 | 0.025 | 0.021 | 0.048 | 2.269 |
| 0.009 | 0.043 | 0.034 | 0.079 | 2.336 |
| 0.013 | 0.059 | 0.046 | 0.111 | 2.417 |
| 0.018 | 0.081 | 0.063 | 0.159 | 2.522 |
| 0.031 | 0.148 | 0.117 | 0.318 | 2.716 |
| 0.04 | 0.2 | 0.16 | 0.477 | 2.979 |
| 0.048 | 0.251 | 0.203 | 0.635 | 3.130 |
| 0.057 | 0.3 | 0.243 | 0.794 | 3.269 |
| 0.065 | 0.347 | 0.282 | 0.953 | 3.380 |
| 0.073 | 0.391 | 0.318 | 1.112 | 3.497 |
| 0.082 | 0.434 | 0.352 | 1.271 | 3.611 |
| 0.095 | 0.478 | 0.383 | 1.430 | 3.733 |
| 0.087 | 0.437 | 0.35 | 1.271 | 3.631 |
| 0.069 | 0.349 | 0.28 | 0.953 | 3.404 |
| 0.051 | 0.253 | 0.202 | 0.635 | 3.146 |
| 0.032 | 0.144 | 0.112 | 0.318 | 2.837 |
| 0.019 | 0.08 | 0.061 | 0.159 | 2.604 |
| 0.012 | 0.044 | 0.032 | 0.079 | 2.482 |
| 0.02 | 0.082 | 0.062 | 0.159 | 2.562 |
| 0.041 | 0.201 | 0.16 | 0.477 | 2.979 |
| 0.058 | 0.301 | 0.243 | 0.794 | 3.269 |
| 0.073 | 0.391 | 0.318 | 1.112 | 3.497 |
| 0.09 | 0.475 | 0.385 | 1.430 | 3.714 |
| 0.101 | 0.5 | 0.399 | 1.509 | 3.782 |

Gyroid (2 / 1 / 3) Sample 1

| P_low (torr) | P_High (torr) | dP (torr) | Throughput (torr*L/s) | Conductance (L/s) |
|---|---|---|---|---|
| 0.004 | 0.04 | 0.036 | 0.048 | 1.324 |
| 0.009 | 0.067 | 0.058 | 0.079 | 1.370 |
| 0.012 | 0.088 | 0.076 | 0.111 | 1.463 |
| 0.017 | 0.123 | 0.106 | 0.159 | 1.499 |
| 0.029 | 0.227 | 0.198 | 0.318 | 1.605 |
| 0.039 | 0.326 | 0.287 | 0.477 | 1.661 |
| 0.048 | 0.419 | 0.371 | 0.635 | 1.713 |
| 0.056 | 0.508 | 0.452 | 0.794 | 1.757 |
| 0.064 | 0.593 | 0.529 | 0.953 | 1.802 |
| 0.073 | 0.675 | 0.602 | 1.112 | 1.847 |
| 0.082 | 0.755 | 0.673 | 1.271 | 1.888 |
| 0.092 | 0.834 | 0.742 | 1.430 | 1.927 |
| 0.099 | 0.873 | 0.774 | 1.509 | 1.950 |
| 0.086 | 0.758 | 0.672 | 1.271 | 1.891 |
| 0.068 | 0.595 | 0.527 | 0.953 | 1.809 |
| 0.059 | 0.51 | 0.451 | 0.794 | 1.761 |
| 0.058 | 0.502 | 0.444 | 0.778 | 1.753 |
| 0.05 | 0.421 | 0.371 | 0.635 | 1.713 |
| 0.031 | 0.231 | 0.2 | 0.318 | 1.589 |
| 0.011 | 0.067 | 0.056 | 0.079 | 1.418 |

Schartz D (2.5 / 2 / 2) Sample 1

| P_low (torr) | P_High (torr) | dP (torr) | Throughput (torr*L/s) | Conductance (L/s) |
|---|---|---|---|---|
| 0.006 | 0.041 | 0.035 | 0.048 | 1.362 |
| 0.01 | 0.066 | 0.056 | 0.079 | 1.418 |
| 0.015 | 0.09 | 0.075 | 0.111 | 1.483 |
| 0.019 | 0.122 | 0.103 | 0.159 | 1.542 |
| 0.032 | 0.221 | 0.189 | 0.318 | 1.681 |
| 0.042 | 0.31 | 0.268 | 0.477 | 1.778 |
| 0.051 | 0.393 | 0.342 | 0.635 | 1.858 |
| 0.059 | 0.47 | 0.411 | 0.794 | 1.933 |
| 0.067 | 0.543 | 0.476 | 0.953 | 2.002 |
| 0.076 | 0.612 | 0.536 | 1.112 | 2.075 |
| 0.086 | 0.681 | 0.595 | 1.271 | 2.136 |
| 0.097 | 0.747 | 0.65 | 1.430 | 2.200 |
| 0.09 | 0.683 | 0.593 | 1.271 | 2.143 |
| 0.071 | 0.545 | 0.474 | 0.953 | 2.011 |
| 0.053 | 0.395 | 0.342 | 0.635 | 1.858 |
| 0.033 | 0.223 | 0.19 | 0.318 | 1.672 |
| 0.013 | 0.069 | 0.056 | 0.079 | 1.418 |

Schartz D (2 / 1 / 3) Sample 1

| P_low (torr) | P_High (torr) | dP (torr) | Throughput (torr*L/s) | Conductance (L/s) |
|---|---|---|---|---|
| 0.005 | 0.076 | 0.071 | 0.048 | 0.671 |
| 0.009 | 0.12 | 0.111 | 0.079 | 0.716 |
| 0.012 | 0.157 | 0.145 | 0.111 | 0.767 |
| 0.017 | 0.219 | 0.202 | 0.159 | 0.786 |
| 0.029 | 0.409 | 0.38 | 0.318 | 0.836 |
| 0.039 | 0.588 | 0.549 | 0.477 | 0.868 |
| 0.048 | 0.757 | 0.709 | 0.635 | 0.896 |
| 0.056 | 0.916 | 0.86 | 0.794 | 0.924 |
| 0.065 | 1.07 | 1.005 | 0.953 | 0.948 |
| 0.073 | 1.217 | 1.144 | 1.112 | 0.972 |
| 0.085 | 1.362 | 1.277 | 1.271 | 0.995 |
| 0.096 | 1.501 | 1.405 | 1.430 | 1.018 |
| 0.078 | 1.221 | 1.143 | 1.112 | 0.973 |
| 0.06 | 0.92 | 0.86 | 0.794 | 0.924 |
| 0.042 | 0.592 | 0.55 | 0.477 | 0.867 |
| 0.02 | 0.223 | 0.203 | 0.159 | 0.783 |
| 0.012 | 0.119 | 0.107 | 0.079 | 0.742 |
| 0.015 | 0.162 | 0.147 | 0.111 | 0.756 |

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