Whether a Bigger Pump Helps Swaps with the Ratio of Mean Free Path to Pipe Diameter

— For air in a pipe of inner diameter **0.025** m and length **1.0** m, the mean free path is **65.673211** nm at atmospheric pressure and **2.661735** times the diameter at **0.1** Pa — the separator is whether gas molecules mostly strike one another or the pipe wall — [Paper 755]

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— From thinking to syncing. —

Abstract

When pumping down, one readily supposes that a bigger pump pumps faster. But a pipe stands between pump and chamber.How much of the pump the pipe eats is counted, divided by the ratio of mean free path to pipe diameter.No new theorem or law is claimed. First, the mean free path grows inversely with pressure——65.673211 nm at atmospheric pressure, 2.661735 times the diameter at 0.1 Pa (Section 2). **Second, molecular-flow conductance does not depend on pressure——1.893418 L/s for this pipe; viscous flow gives 0.529689 L/s per pascal of mean pressure** (Section 3). **Third, the two formulas cross in the transition regime——at a mean pressure of 3.574581 Pa, where the ratio is 0.074463** (Section 3). **Fourth, and this is the core. Whether ten times the pump helps swaps with regime——effective speed rises 1.001704 times in molecular flow, 1.452739 times in viscous flow** (Section 4). **Fifth, how pipe diameter acts swaps too——doubling the diameter gives 8.000000 times in molecular flow, 16.000000 times in viscous flow** (Section 4). **Sixth, the separator is whether gas molecules mostly strike one another or the pipe wall——"a bigger pump pumps faster" has no truth value until that ratio is stated** (Section 5).
Keywords: mean free path, Knudsen number, conductance, effective pumping speed, molecular and viscous flow, vacuum piping.

Scope of this paper (scope note): **No new theorem or law is claimed——the mean free path formula, dividing flow regimes by Knudsen number, molecular- and viscous-flow conductances of a round pipe, and combining pump and pipe in series are all known (O'Hanlon 2003, Lafferty 1998).No transition-flow formula is used——the point where the two formulas agree is shown only as a guide to the boundary; the correct conductance there is not derived.Ultimate pressure is not treated——outgassing, leaks and ultimate pressure are not treated; only pumping speed is considered.One gas——air is treated as a single molecular species with a representative diameter of 3.7×10^{-10} m.Regime boundaries are conventions——dividing at ratios 0.01 and 0.5 into three regimes is a widely used guide.No real equipment is claimed——particular pumps and pipework are not treated.Relation to earlier papers**: **Paper 722 showed that the same water can be stopped and passed because pore radius enters the two transports at different powers——its scope note stated that Knudsen diffusion was not treated, and that the estimate breaks down where the radius is of the order of the mean free path. This enters where it breaks down, counting how the power of pipe diameter changes from 4 in viscous flow to 3 in molecular flow, and how even the value of the pump swaps.Paper 540 is also cited——there series stiffness was the harmonic mean, dominated by the weaker part. Effective pumping speed is the same series combination, and where conductance is small, the pump does not help.**What is added is **tabulating mean free path and regime by pressure**, **showing that the two conductances agree inside the transition regime**, **showing that ten times the pump yields $\mathbf{1.001704}$ and $\mathbf{1.452739}$ times by regime**, and **placing the separator on whether molecules strike one another or the wall**.

1. Notation and the Question

Setting: **let the mean free path at temperature T, molecular diameter d_m and pressure P be λ, and divide flow by its ratio to pipe diameter D, the Knudsen number λ/D. The conductance of a round pipe of length L takes the forms below in molecular and viscous flow. With pump speed S and pipe conductance C in series, the chamber sees S_{eff}.**

$$\lambda = \frac{kT}{\sqrt{2}\,\pi d_m^2 P}, \qquad C_{\text{mol}} = \frac{\pi}{12}\,\bar{v}\,\frac{D^3}{L}, \qquad C_{\text{vis}} = \frac{\pi D^4 \bar{P}}{128\,\eta L}, \qquad \frac{1}{S_{\text{eff}}} = \frac{1}{S} + \frac{1}{C}$$

Take $T = 293.15$ K, $d_m = 3.7 \times 10^{-10}$ m, $D = 0.025$ m, $L = 1.0$ m and air viscosity $\eta = 1.81 \times 10^{-5}$ Pa s. The mean speed $\bar{v}$ is 462.868739 m/s. Ratios below 0.01 are viscous flow, 0.5 and above molecular flow, and between them transition flow.

Question: **does a bigger pump pump the chamber down faster?**

2. The Mean Free Path Grows Inversely with Pressure

Computation 2.1: **mean free path and its ratio to the diameter were derived at each pressure.**

pressure	mean free path	ratio to diameter	regime
101325 Pa	6.567321×10^{-8} m	2.626928×10^{-6}	viscous
1000 Pa	6.654338×10^{-6} m	2.661735×10^{-4}	viscous
10 Pa	6.654338×10^{-4} m	2.661735×10^{-2}	transition
0.1 Pa	6.654338×10^{-2} m	2.661735	molecular
10^{-3} Pa	6.654338 m	2.661735×10^{2}	molecular
10^{-8} Pa	6.654338×10^{5} m	2.661735×10^{7}	molecular

> **Observation 2.2**
>
> **the single word “vacuum” spans regimes from molecules striking one another to molecules striking only walls.The mean free path is 65.673211 nm at atmospheric pressure but 2.661735 times the diameter at 0.1 Pa——in the same pipe, the type of flow swaps with pressure.**

3. Two Flows, Two Conductances

Computation 3.1: **the pipe’s conductance was derived by both formulas, and the mean pressure where they agree was found.**

quantity	value
molecular-flow conductance	1.893418 L/s
viscous-flow conductance (per pascal of mean pressure)	0.529689 L/s
mean pressure where they agree	3.574581 Pa
ratio there	0.074463 (transition)
viscous flow at 1000 Pa	529.689499 L/s

Observation 3.2

molecular-flow conductance does not depend on pressure; viscous-flow conductance is proportional to it.The two formulas agree inside transition flow, at a ratio of 0.074463——they cross where neither can be used correctly, so the crossing is only a guide to the boundary.

4. Whether a Bigger Pump Helps Swaps

Computation 4.1: for three pump speeds, effective pumping speed was derived in molecular flow and in viscous flow at a mean pressure of 1000 Pa.

pump	effective, molecular	effective, viscous (1000 Pa)
100 L/s	1.858234 L/s	84.119157 L/s
1000 L/s	1.889840 L/s	346.272560 L/s
10000 L/s	1.893060 L/s	503.043797 L/s

Observation 4.2

this is the core: whether ten times the pump helps swaps with regime.From 1000 to 10000 L/s, the effective speed rises 1.001704 times in molecular flow and 1.452739 times in viscous flow——in molecular flow the pipe caps it at 1.893418 L/s, and no pump, however large, gets past.

Observation 4.3

how diameter acts swaps too.Doubling the diameter multiplies conductance by 8.000000 in molecular flow and 16.000000 in viscous flow——the powers of diameter differ, 3 and 4, and in molecular flow a wider pipe helps where a bigger pump does not.

5. The Separator

Observation 5.1

the separator is whether gas molecules mostly strike one another or the pipe wall, that is, the ratio of mean free path to diameter (the Knudsen number).Where they strike one another, a bigger pump helps; where they strike the wall, the pipe decides——"a bigger pump pumps faster" has no truth value until that ratio is stated.

Observation 5.2

beside Paper 722.Paper 722 showed pore radius entering liquid and vapour transport at different powers, and stated that the estimate breaks down at the scale of the mean free path——this is beyond that point, where the power of diameter changes from 4 to 3 and the value of the pump swaps.

Observation 5.3

beside Paper 540 as well.Paper 540 showed series stiffness to be the harmonic mean, dominated by the weaker part——effective pumping speed is the same series combination: a 1000 L/s pump with a 10 L/s pipe gives 9.900990 L/s. The weaker part decides in both, and here the flow regime decides which part is weaker.

Observation 5.4

what is not said.The correct transition-flow formula, outgassing, ultimate pressure and real equipment are not treated——what is shown is that whether pump or pipe matters swaps with the ratio of mean free path to pipe diameter.

6. Roll Call and Closing

1. **65.673211 nm at atmospheric pressure** (Observation 2.2): **molecules strike one another.**
2. **2.661735 times the diameter at 0.1 Pa** (Computation 2.1): **molecules strike the wall.**
3. **molecular 1.893418 L/s** (Computation 3.1): **independent of pressure.**
4. **viscous 0.529689 L/s per pascal** (Computation 3.1): **proportional to pressure.**

5. **crossing at 3.574581 Pa** (Computation 3.1): **inside transition flow.**
6. **1.001704 times in molecular flow** (Observation 4.2): **the pump does not help.**
7. **1.452739 times in viscous flow** (Observation 4.2): **the core.**
8. **8.000000 times for double diameter** (Observation 4.3): **molecular.**
9. **16.000000 times** (Observation 4.3): **viscous.**
10. **one another, or the wall** (Observation 5.1): **the separator; Paper 722 and Paper 540.**

Closing: **Whether a bigger pump helps swaps with the ratio of mean free path to pipe diameter.In a pipe of inner diameter 0.025 m, the mean free path grows from 65.673211 nm at atmospheric pressure to 2.661735 times the diameter at 0.1 Pa, and flow in which molecules strike one another becomes flow in which they strike only the wall——molecular-flow conductance is 1.893418 L/s regardless of pressure, viscous flow gives 0.529689 L/s per pascal, and the two formulas cross at 3.574581 Pa inside transition flow.Raising the pump from 1000 to 10000 L/s lifts effective speed only 1.001704 times in molecular flow but 1.452739 times in viscous flow at 1000 Pa——in molecular flow the pipe caps it, and even diameter acts differently, 8.000000 times for double diameter against 16.000000 in viscous flow.The separator is whether gas molecules mostly strike one another or the pipe wall——"a bigger pump pumps faster" has no truth value until that ratio is stated.Placed among the earlier papers——Paper 722 stated that its estimate breaks down at the scale of the mean free path, and this counts what lies beyond. In the series combination of Paper 540, the flow regime decides which part is weaker.To be honest——the correct transition-flow formula, outgassing and ultimate pressure are not treated, and air is taken as one molecular species.**

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