Driving (pre)-planetary Bodies by Knudsen Engine Studies

Planet Formation and Evolution

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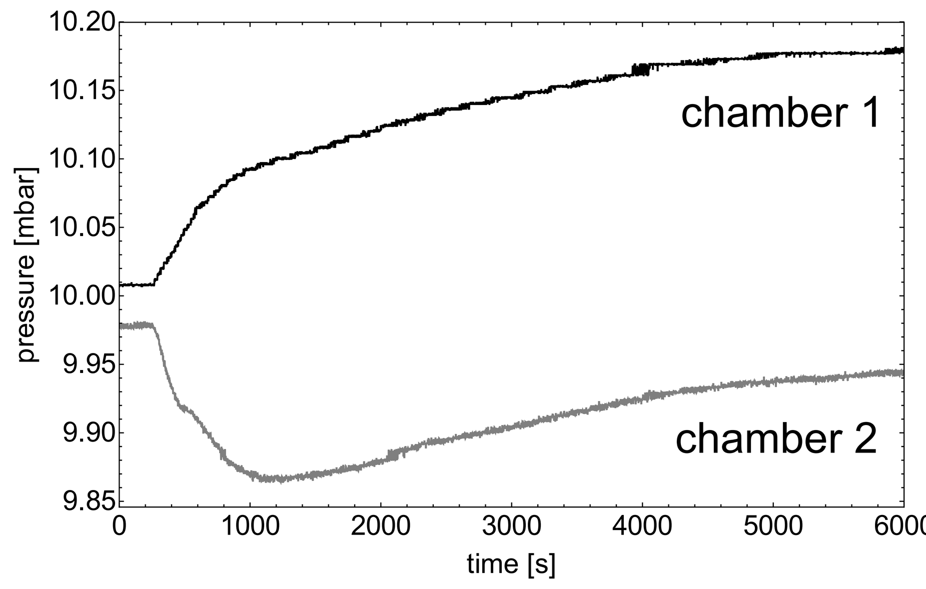
Abstract

It was just recently discovered that dusty (pre)-planetary bodies, non uniformly heated, effectively transport gas through their pores [1]. As Knudsen compressor thermal creep efficiently pumps gas from cooler to hotter dust layers [2]. Applied to protoplanetary disks, this gas flow can act as an engine and contribute to the transport of pre-planetary matter which is heated one way or the other (radioactive decay, radiation,...). We carried out first laboratory experiments to quantify these gas flows. We measured the pressure differences in two chambers connected by a dust filled tube. The dust is heated at one side by radiation. We probed different size distributions in the micrometer range and varied the ambient pressure. As dust samples we used the martian analogue material JSC Mars 1A and spherical glass particles.

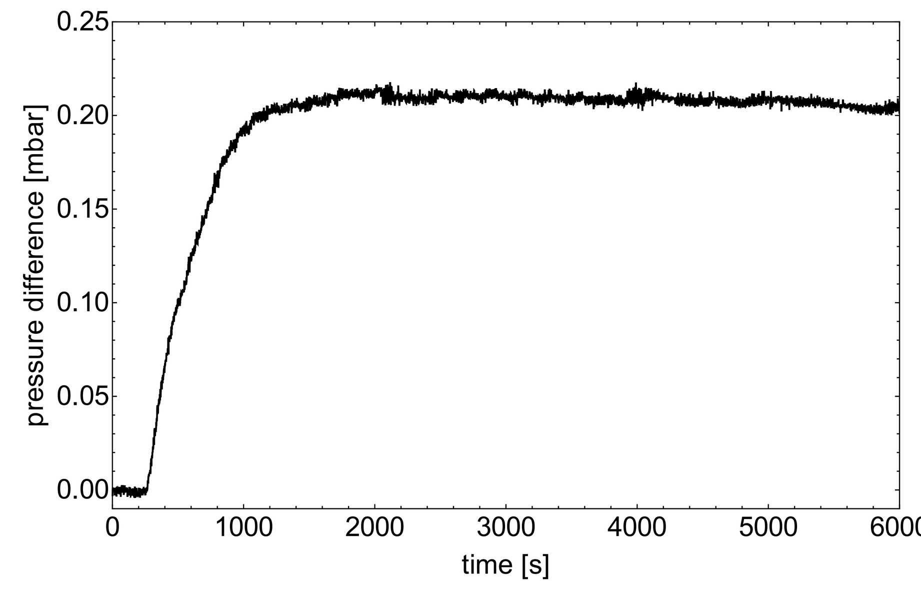
Measurements

On the right side is an example for a pressure measurement with JSC Mars 1A at an ambient pressure of 10 mbar. The dark line shows the pressure of chamber 1, the light gray line of chamber 2. It is clearly visible that during the first 1000 seconds the pressure falls in chamber 2 and rises in chamber 1 because of the pumping process.



Shown on the right is the pressure difference between chamber 1 and 2. After about 1500 seconds the maximum pressure difference according to Eq. (1) is reached and stays at the same level until the end of the measurement.

In our experimental setup the maximum pressure change is at 0.06 Pa/s, which corresponds to a mass flow rate of about 8×10^{-7} kg/(s m^2).



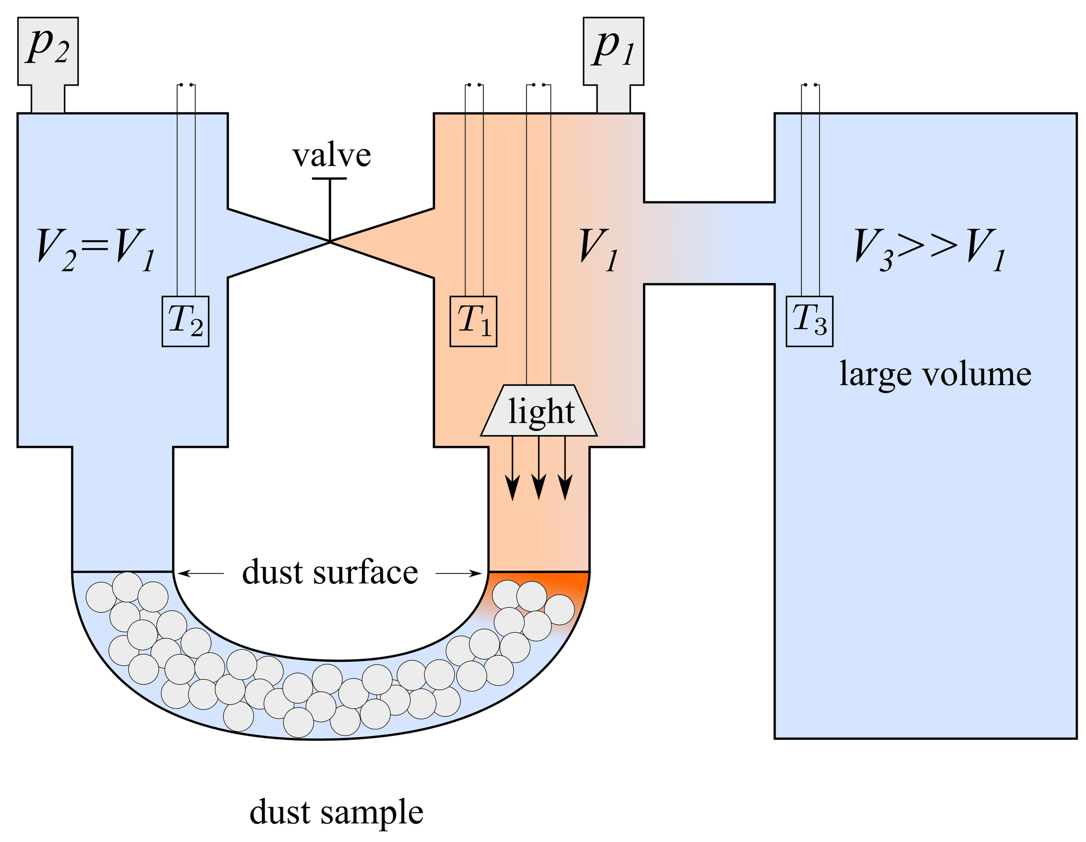
Experimental Setup

Two vacuum chambers 1 and 2 with volumes V_1 and V_2 are connected by a U-formed tube (diameter: 40 mm; lenght: 20cm). A halogen lamp above the dust surface at one side of the tube provides radiation (~ 2500 W/m^2) which induces a temperatur gradient within the dust. Due to the temperature difference on the inlet and outlet of the dust thermal creep flow is active and gas is pumped from the colder to the warmer chamber. The pressures p_1 and p_2 in both chambers are measured over a time period of ~ 2 hours. The absolute starting pressure is varied from 0.1 mbar up to 50 mbar. To realize an almost constant pressure during the measurements in chamber 1, it is connected with a large chamber with volume $V_3 >> V_1$.

In theory [3] the maximum pressure difference Δp_{max} is given by

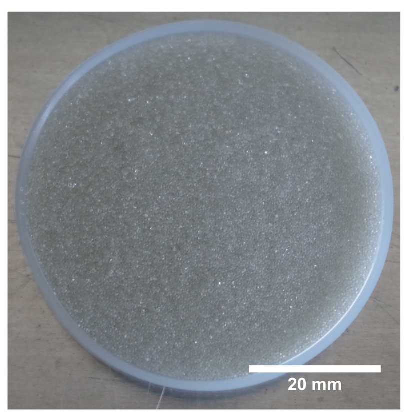
$$\Delta p_{\max} = p_{\rm avg} \frac{\Delta T}{T_{\rm avg}} \frac{Q_T}{Q_P}, \qquad (1)$$

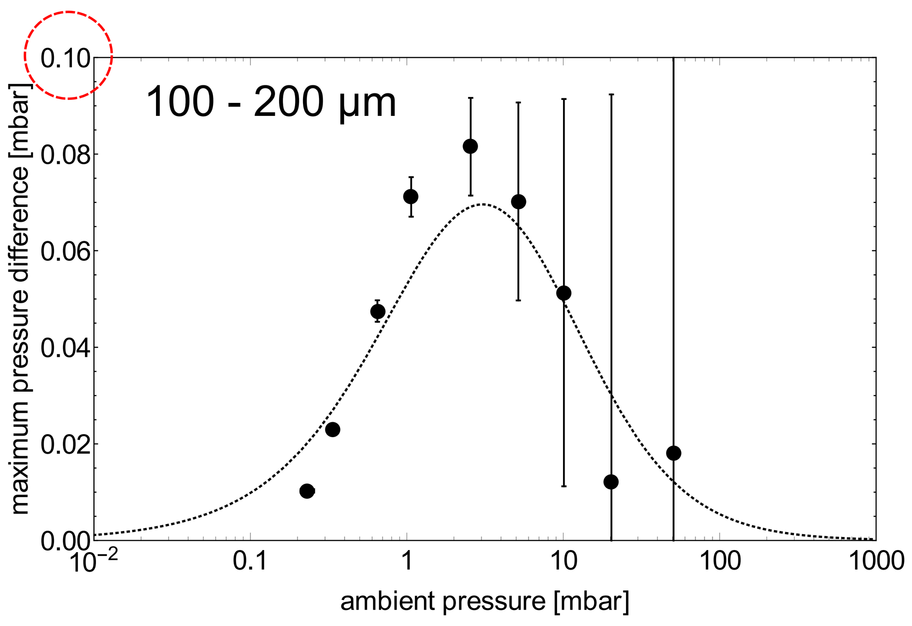
where $\Delta T = T_{hot} - T_{cold}$ is the temperature difference and T_{avg} the average temperature between the hot dust surface in chamber 1 and the cold in chamber 2. p_{avg} is the average pressure (ambient pressure) and Q_T/Q_P coefficients of thermal creep and back flow.

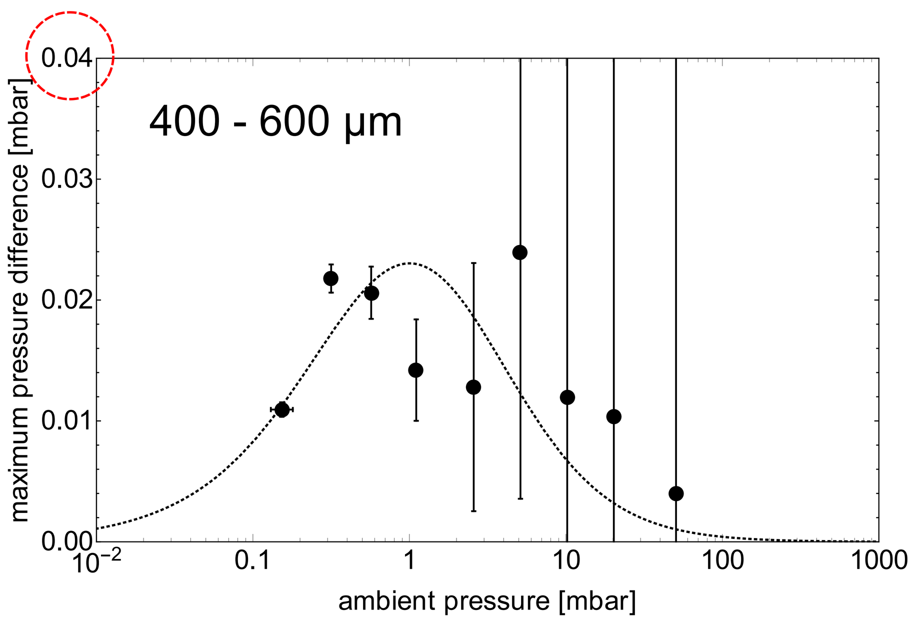


Results

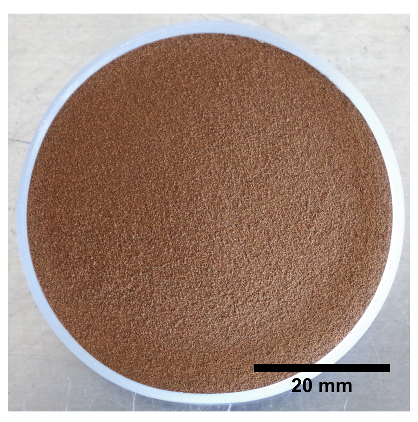
spherical glass particles

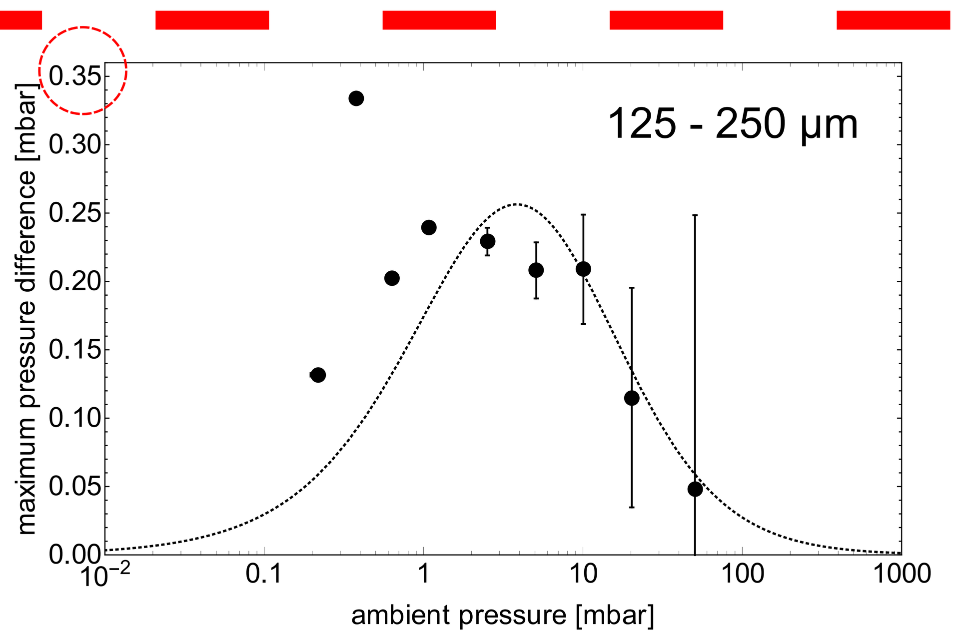




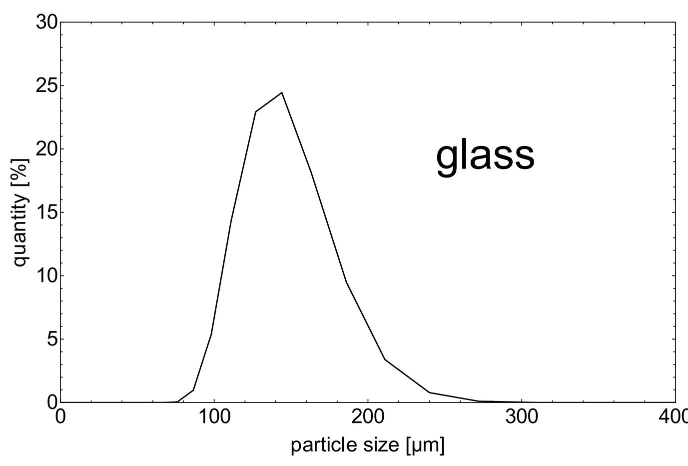


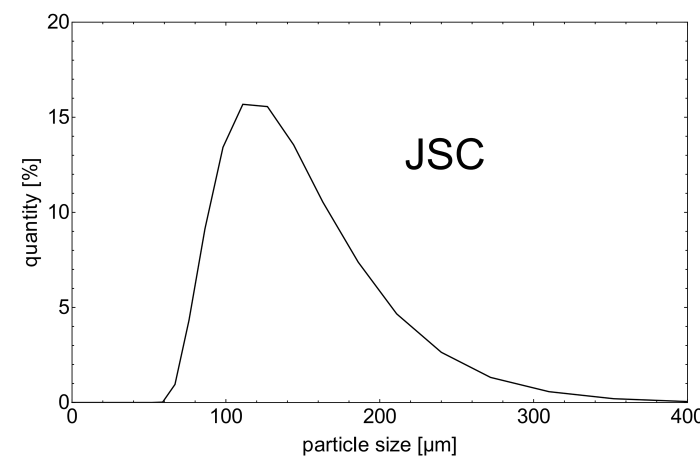
JSC Mars 1A





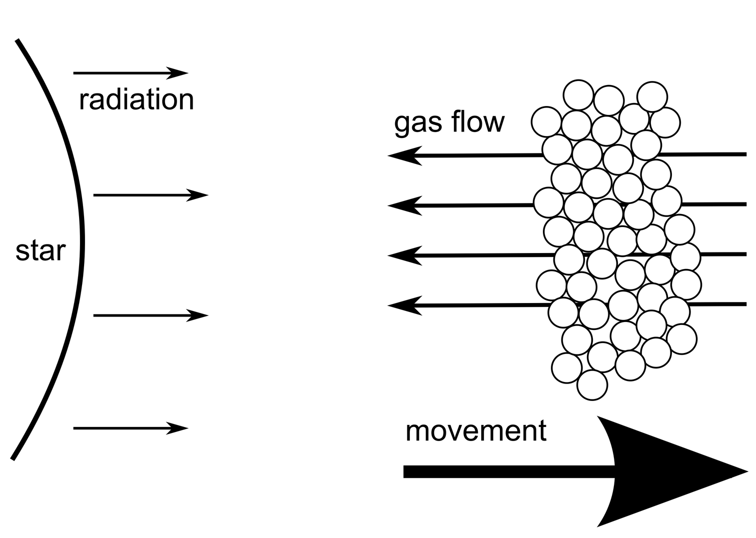
The three figures on the left side show the maximum pressure difference Δp_{max} reached through the Knudsen compressor for spherical glass particles with different size distributions and JSC Mars 1A dust. The black dotted lines represent the fit function Eq. (1) with T_{hot} as free fit parameter. To get a more realistic fit function an additional particle size analysis was made for every dust sample. Two size distributions are shown below.





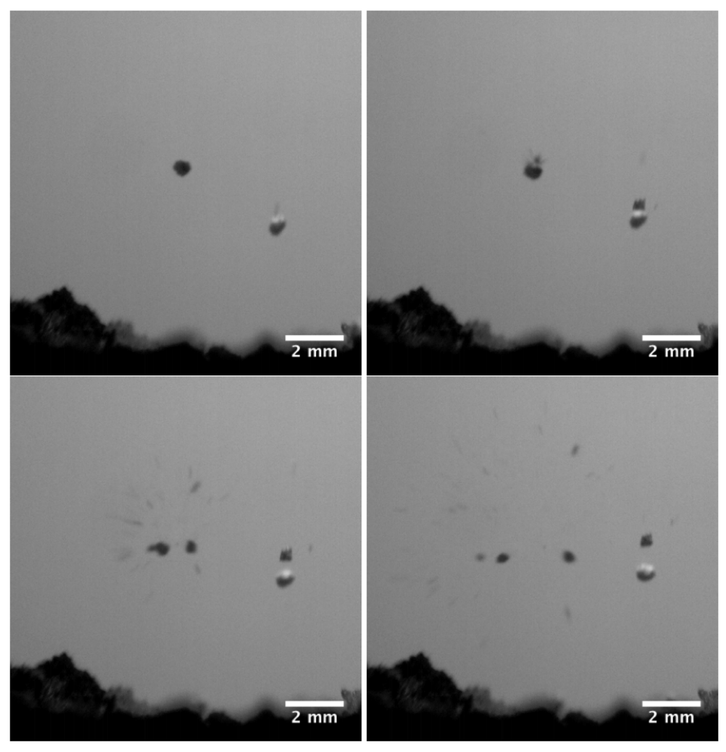
Our measurements are in accordance with the theoretical pressures from Eq. (1). T_{hot} reveals that the temperature strongly depends on the used dust sample. The surface temperature is at ~ 374 K for the glass particles and ~ 626 K for the JSC Mars 1A (for the same light intensity).

Application



A porous body in a protoplanetary disc is heated on one side by the radiation of the star, which induced the Knudsen engine gas flow through its pores and pushes it in a farther orbit.

Overpressure inside a porous body leads to explosion and total destruction (timestep t = 2 ms).



References

[1] De Beule C. et al. (2013) NPHYS, 2821

[2] Knudsen M. (1909) Annalen der Physik, 336, 633-640

[3] Muntz et al. (2002) JVST, A, 20, 214

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