Piezo-thermal effect in gas and plasma

J.C. Waybright[1,2], E.J. Kolmes[2], S. Davidovits[2], I.E. Ochs[2], N.J. Fisch[2]

[1]South Dakota State University, Brookings, SD 57007
[2]Princeton Plasma Physics Laboratory, Princeton, NJ 08540

Piezo-thermal Effect

- When compressed, a gas immersed in a potential field has been predicted to develop a temperature differential [1].

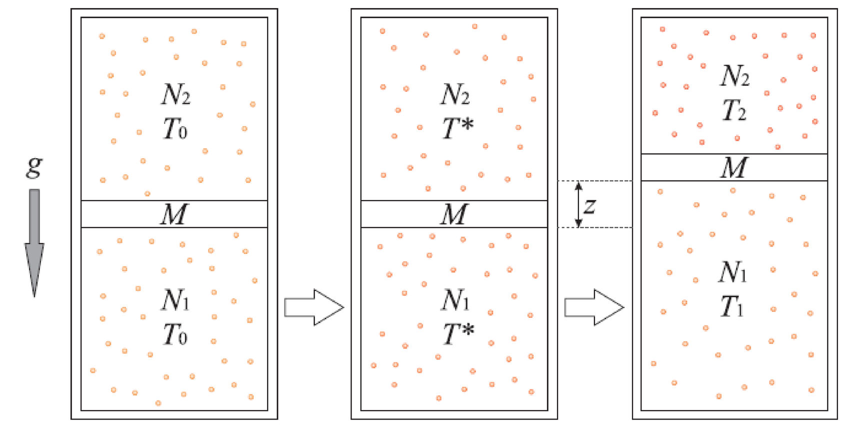

Figure 1: Description of piezo-thermal effect for gas heated from T_0 to T^* separated by a partition of mass M [1].

- Hot and cold regions develop at locations of maximum and minimum potential energy respectively.

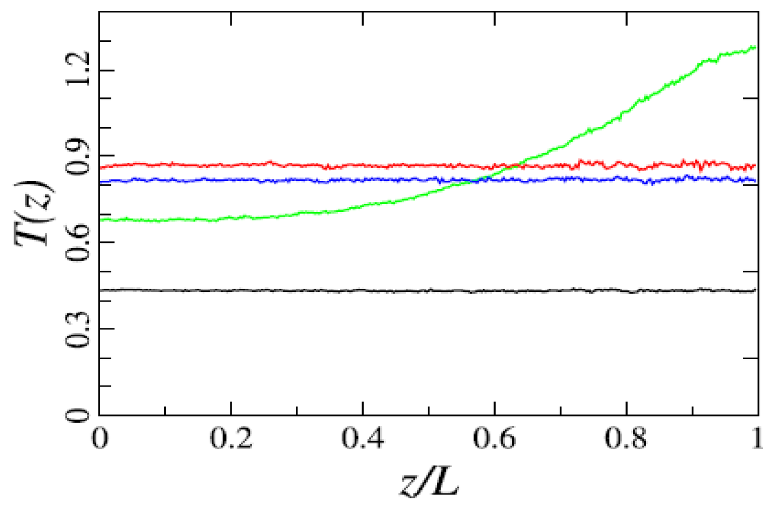

Figure 2: Temperature profile for fast compression from Geyko. Black: initial profile; red: upon heating; green: at maximum temperature gradient; blue: at new equilibrium [1].

- Effect confirmed through hard sphere simulations of neutral gas in gravitational and centrifugal potentials, although theory extends to any generalized potential field.

Research Goals

- **Develop simulation to model Piezo-thermal effect for coulomb collisions in a gravitational potential and compare with previous results for hard-sphere collisions.**
- **Observe the effects that altering interaction strength has on the temperature profile.**
- **Look for evidence of population inversion upon cooling.**

Computational Methods

- System divided up into cells perpendicular to the potential to be used for collision pair decision and calculating local temperature and density.
- Adiabatic compression was modeled by initializing particle velocities to a Maxwell-Boltzmann distribution set at a temperature (T^*) greater than that used for the spatial distribution (T_0).

$$n(z) = n_0 e^{-mgz/T_0}$$
$$f(v) = \left(\frac{m}{2\pi T^*}\right)^{1/2} e^{-\frac{mv^2}{2T^*}}$$

- Dimensionless parameters G and δ set scale height and compression magnitude defined as the following

$$G = \frac{mgL}{T_0} \qquad \delta = \frac{T^* - T_0}{T_0}$$

- A binary collision operator outlined by Nanbu was used to simulate coulomb collisions [2]. This technique models several small-angle collisions as a single, cumulative scattering angle.
- Isotropy parameter s is calculated and used to generate the cumulative scattering angle (χ) for each collision pair. This is dependent on the ratio of the mean free path to system length (l_m/L), local temperature ($\tilde{T}$), time step ($\Delta\tilde{t}$), and relative velocity ($\tilde{v}_r$). Here, C is a dimensionless constant.

$$s = C\left(\frac{l_m}{L}\right)^{-1} \frac{\tilde{T}^{3/2}\Delta\tilde{t}}{(\tilde{v}_r)^3}$$

- Small values of s generate a Gaussian distribution of χ with a narrow width. Large s generates the distribution $f(\chi) \approx \sin\chi/2\pi$ [2].

Temperature Profile

- A similar temperature profile was seen under the coulomb collision operator compared to hard sphere collisions.
- Highly collisional simulations resulted in the largest temperature gradients and least overall damping.
- Temperature gradient oscillates at approximately the sound frequency ($1/t_s$).

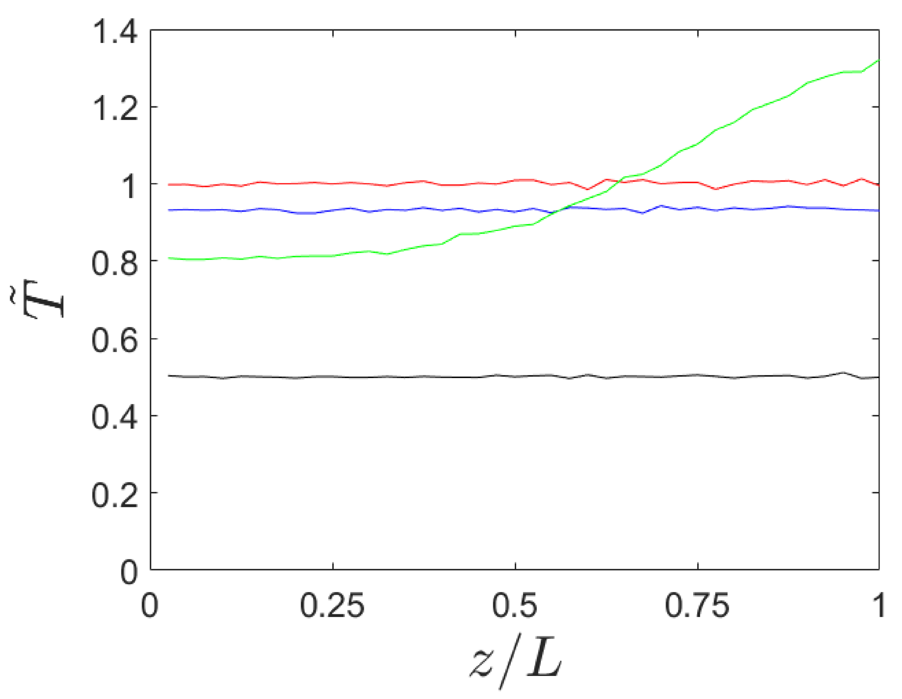

Figure 3: Temperature profile for fast compression using coulomb collisions. Black: initial profile; red: upon heating; green: at maximum temperature gradient; blue: at new equilibrium. $G = 2.5$, $\delta = 1$

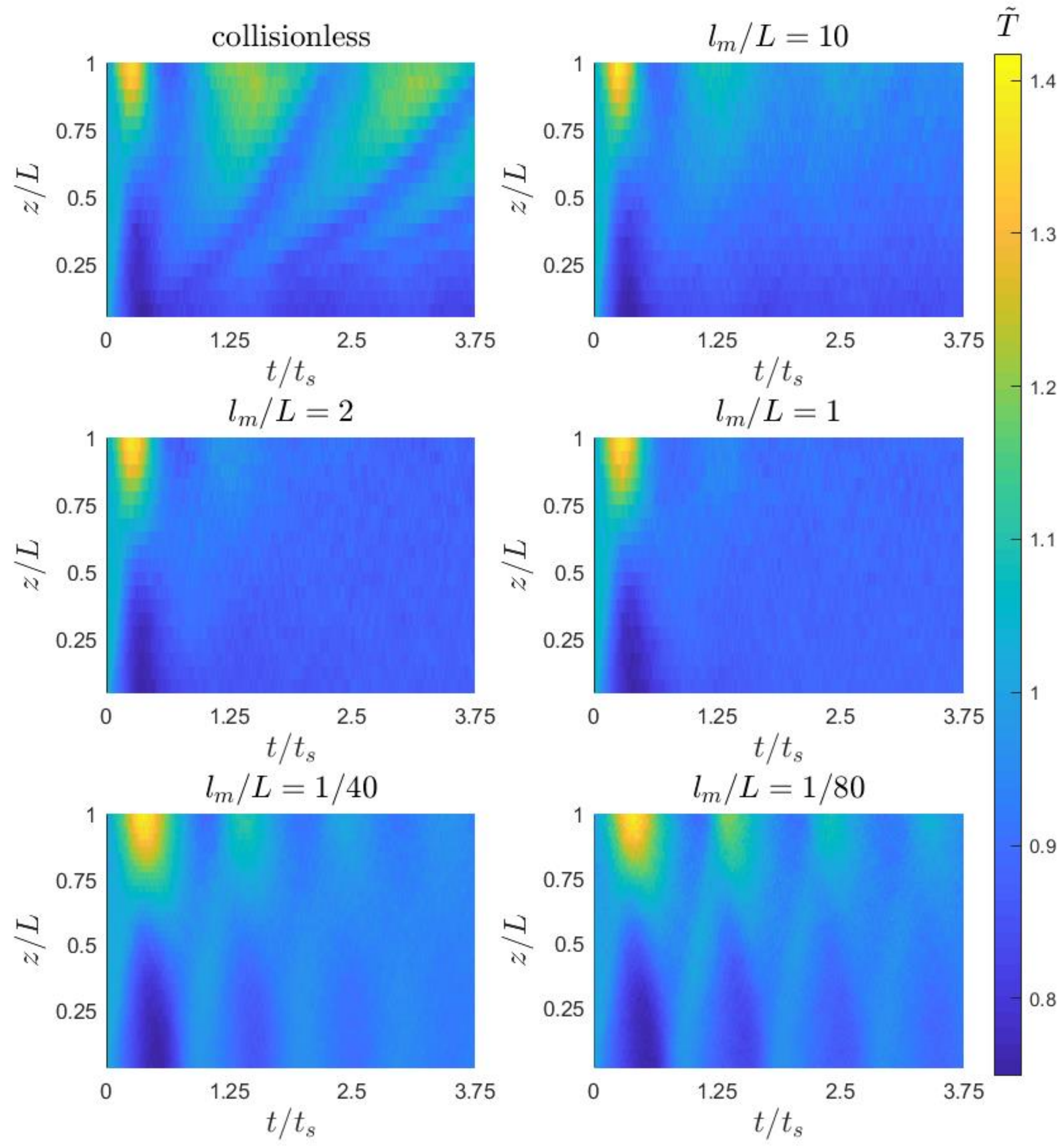

Figure 4: Temperature profiles over time for several values of l_m/L. Time variable has been normalized to the sound time (t_s). $G = 2.5$, $\delta = 1$

Population Inversion

- Under the coulomb collision operator, high speed particles do not interact as strongly with less energetic particles. As a species cools via collisions, this may result in a distinct population near the tail of the distribution.
- This effect is clearly seen by rejecting collisions from pairs with relative velocities beyond a cutoff.

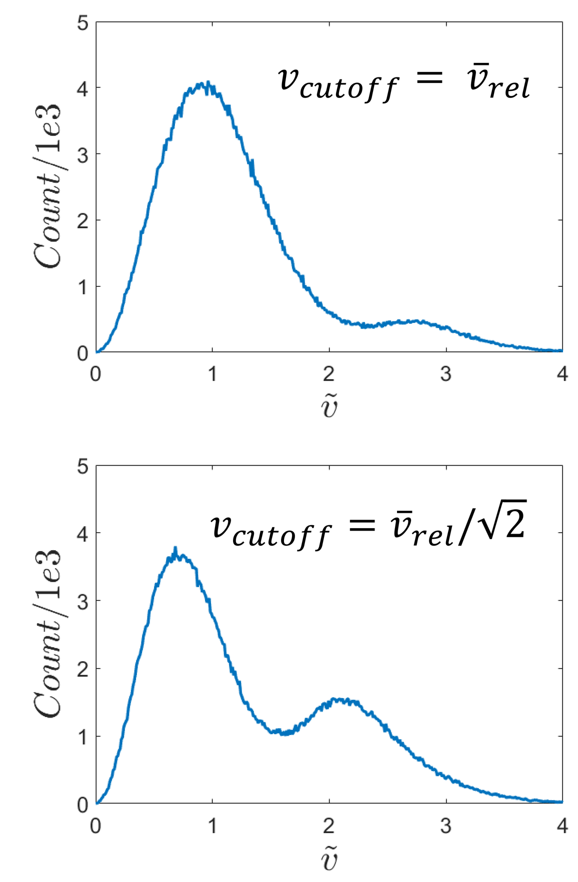

Figure 5: Speed distribution after cooling for 10 sound times using two different values for the cutoff relative velocity. No compression or potential was used.

Conclusions

- Piezo-thermal effect identified in a system of particles in a gravitational potential that interact via coulomb collisions.
- Population inversion seen under a modified collision operator.
- Future work is aimed at identifying a population inversion in cooling species during piezo-thermal effect.

Acknowledgement

This work was made possible by funding from the Department of Energy Workforce Development for Teachers and Scientists (WDTS) for the Summer Undergraduate Laboratory Internship (SULI) program. This work is supported by the US DOE Contract No. DE-AC02-09CH11466

References

1. V.I. Geyko and N.J. Fisch, Phys. Rev. E **94** 042113 (2016).
2. K. Nanbu, Phys. Rev. E **55** 4642 (1997).

Piezo-thermal effect in gas and plasma

J.C. Waybright, E.J. Kolmes, S. Davidovits, I.E. Ochs, N.J Fisch

When compressed, a gas immersed in a potential field has been predicted to develop a temperature differential [1]. This phenomena, called the piezo-thermal effect, results in hot and cold regions corresponding to the locations of the maximum and minimum potential energy respectively. Previous numerical simulations confirmed this temperature differential for centrifugal and gravitational potentials. Although plasma features a number of complications, similar effects might also be imagined in compressing plasma. In this study, the effect was investigated using a coulomb collision operator and adjusting the interaction strength between particles. The behavior of the temperature differential was similar to that of the neutral gas case, and the damping of its oscillation was heavily dependent on setting the ratio of mean free path to system length, l_m/L. A population inversion was also seen under a modified collision operator and is the aim for future research.

[1] V.I. Geyko and N.J. Fisch, Phys. Rev. E 94 042113 (2016).