RAGE Simulations of Radiation Driven Turbulence

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1. Introduction

Turbulent hydrodynamic behavior driven by radiation is an important issue to several areas of high energy density plasma physics. To study this topic simulations of a series of test problems with the RAGE radiation-hydrodynamics computer code were performed. The test problems are essentially a hot, low density region adjacent to a cool, high density region. The two regions meet at a perturbed interface. The hot region starts at 1.5 keV and 1 g/cm^3. The cool region starts at 0.2 keV and 10 g/cm^3.

One of the sample problems is shown in Figures 1 and 2. The interface consists of two modes: one which is four wavelengths across the problem and one which is nine wavelengths. The amplitude of the shorter wavelength mode is one half of the wavelength of the longer wavelength mode.

Three problems have been run, each of a different physical size but with the same physical properties. The purpose of this parametric study is to test the relative effects of radiative heat transfer on the growth of fluid instabilities. Since the physical properties of the materials are the same in all cases, the radiation mean free paths and the rate that radiative energy moves throughout the problem is kept constant. The physical size of the three problems varies by two orders of magnitude. One problem is on a mesh that is 0.1 cm wide and 0.2 cm long. Another is 1.0 cm x 2.0 cm and a third is 10 cm x 20 cm. One expects that the larger problems will see a decreasing role of radiation transport.

2. Computational Model

The RAGE radiation hydrodynamic computer code was used to study three systems of radiation-driven fluids. RAGE is a 1, 2, or 3-D adaptive mesh refinement code. It is written and maintained by Los Alamos National Laboratories and SAIC. In these problems, the mesh consists of 2-D squares that are divided or combined as the complexity of the mesh changes. In these problems the total number of mesh cells gets as large as 500,000.

Radiation transport in these problems is by gray diffusion. Analytic opacity and equation-of-state models are used. An analytic equation of state model has been used. RAGE allows one to specify that the plasma pressure is

$$P\ (\mathrm{Pa}) = \kappa_a\ (\rho/\ \rho_o - 1) + a\ \rho\ \varepsilon,$$

where κ_a is a constant, ρ is the mass density (g/cm^3), ρ_o is a reference density, and a is another constant. ε is the specific energy density defined by

$$\varepsilon\ (\mathrm{erg/g}) = C_v\ (\mathrm{erg/g\text{-}eV})\ (T\ (\mathrm{eV}) - T_o\ (\mathrm{eV}))\ ,$$

where C_v is the specific heat and T_o is a reference temperature. The gray opacity is also analytic,

$$\sigma\ (\mathrm{cm^2/g}) = C\ (T_z/T\ (\mathrm{eV}))^3 + \sigma_{scat}\ ,$$

where C is a constant, T_z is a reference temperature (eV), and σ_{scat} is a constant.

In these calculations, there two material types with the parameters shown in Table I.

3. Post-Processing of RAGE Results

The RAGE calculations have been post-processed to extract information that can be compared with other results. Line integrals need to be performed across the mesh in the direction transverse to the shock motion. This is in the narrow direction of the problem. To date, line integrals of mass density, material temperature, and radiation temperature are performed. Two methods were attempted to do this. A post-processing code was obtained from LANL that can read special output files created by RAGE. A new feature was written into the code to do the line integrals called for. Considerable effort was put into this and the code is still not working. It became clear that we needed to get results in a timely manner, so we generated line integrals with the LANL POP code.

4. Results

The results of the three RAGE calculations are shown in Figures 3 through 27. RAGE calculations were run until the flow reached the terminal end of the problem mesh. The three problem meshes are 0.2 cm, 2.0 cm and 20 cm in length and take successively more time to run.

In Figures 3 through 8, mass density and material temperature contours of the three runs are shown shortly before the flow reaches the terminal ends of their meshes. The contours are plotted at 22 ns, 220 ns, and 2.2 μs. Radiation temperature contours are not shown because they are the same as the material temperatures in these problems. Figures 3 and 4 show the results for the small 0.1 cm by 0.2 cm problem. Because the radiation mean free path is large compared to the problem size relative to the other problems, much of the detail of the fluid instabilities has eroded away. In Figures 5 and 6, the results from the 1.0 x 2.0 cm problem are shown. Here, much more structure remains because the radiation mean free path is relatively short compared to the mesh size by an order of magnitude. Finally, the results of the large 10 x 20 cm problem are shown in Figures 7 and 8, where even more detail persists. But in all three cases, four prominences persist. This is the same as the larger amplitude perturbations on the original interfaces. The shorter-wavelength, smaller-amplitude perturbation disappears.

The line-outs and line integrals are shown in Figures 9 through 27. Because the problems are all symmetric about their centerlines, the line-outs and integrals are only performed across half of the problem. First, the line-outs and integrals for the 10 x 20 cm problem at 2.2 μs are shown in Figures 9 through 15. The line-out and integrals are only done from 0 to 5 cm even through the mesh goes to 10 cm, because of the symmetry issue. The mass density line-outs are shown in Figure 9 along six slices transverse to the direction of flow. These are at 2, 4, 6, 8, 10, and 12 cm from the terminal end of the problem. It is clear that there is a large amount of structure in the problem at this time. In the 2 cm line-out the remnants of the shorter wavelength structure is shown, but it disappears in the 4 cm line-out. In Figure 10, the mass density line-outs and line integrals are shown for 2 cm and 4 cm slices. This is a demonstration that POP is doing the line integrals as expected. At 2 cm, the line integral is 11.7 g/cm^2, which is the maximum and rightmost value on the integral curve. At 4 cm, the line integral is 34.0 g/cm^2. The average values are therefore 2.34 and 6.8 g/cm^3. All six mass density line integrals are shown in Figure 11. Similarly, in Figures 12 through 15 the line-outs and line integrals are shown for material and radiation temperatures. Once again, the radiation and material temperatures are the same. In Figures 16 through 21, the same procedure is followed for the 0.1 cm x 0.2 cm problem. As expected, there is less structure than in the large mesh problem. The line-outs and integrals are shown for the 1.0 cm x 2.0 cm problem in Figures 22 through 27. Notice that in all cases the final two lines lay atop each other because those slices are beyond the region where the bubbles and spikes exist. The line-averaged values for mass density, material temperature, and radiation temperature are listed for all three problems in Tables II, III, and IV.

5. Conclusions

Three radiation driven fluid instability problems have been simulated with the RAGE computer code. Keeping the material properties the same (density, temperature, opacity), the size scale of the problems was separated by one and then two factors of 10. The effect of radiation transfer on the structure of the bubble and spike system of the fluid instability was markedly changed by the changes in size scale. The large problem was very complex because the radiation mean free path was smaller than the size of the structures. The small problem was smoothed by “fire-polishing” by the radiation. Line-out were taken and line-averaged densities and temperatures were recorded for comparison with other methods of analysis.

Acknowledgements

The authors wish to thank R.P. Weaver (LANL, X-2), M.L. Gittings (SAIC), and Mike Clover (SAIC) for the use of the RAGE code and for help with these calculations. The RAGE calculations were run on LANL computers, for which the authors are thankful. They also wish to thank John Scott and Joyce Takamine with help in the post-processing of the RAGE results. Finally, the authors are thankful to Charlie Nakhleh (LANL, X-2) for help in getting this project started.

Table I. Material parameters

Material	κa (erg/g-eV)	ρo (g/cm^3)	a	C_v (erg/g-eV)	T_o (eV)	C (cm^2/g)	T_z (eV)	σ_{scat} (cm^2/g)
1 (hot)	8.e10	1.0	0.1	8.e10	0.1	1.e4	1000.	0.2
2 (cold)	6.4e10	1.0	0.1	6.4e10	0.1	1.e5	1000.	0.2

Table II. Line averages for 0.1 cm x 0.2 cm problem at 22 ns

Slice Position (cm)	Average Mass Density (g/cm^3)	Average Material Temperature (keV)	Average Radiation Temperature (keV)
0.02	0.2	0.16	0.16
0.04	6.8	0.25	0.25
0.06	8.7	0.56	0.56
0.08	5.3	0.81	0.81
0.10	2.2	0.99	0.99
0.12	2.2	0.99	0.99

Table III. Line averages for 1.0 cm x 2.0 cm problem at 220 ns

Slice Position (cm)	Average Mass Density (g/cm^3)	Average Material Temperature (keV)	Average Radiation Temperature (keV)
0.2	1.52	0.24	0.24
0.4	8.3	0.48	0.48
0.6	5.9	0.68	0.68
0.8	5.5	0.79	0.79
1.0	3.4	0.95	0.95
1.2	3.4	0.95	0.95

Table IV. Line averages for 10 cm x 20 cm problem at 2.2 μs

Slice Position (cm)	Average Mass Density (g/cm^3)	Average Material Temperature (keV)	Average Radiation Temperature (keV)
2.0	2.34	0.24	0.24
4.0	6.8	0.68	0.68
6.0	7.0	0.71	0.71
8.0	6.6	0.76	0.76
10.0	2.6	0.86	0.86
12.0	2.6	0.86	0.86

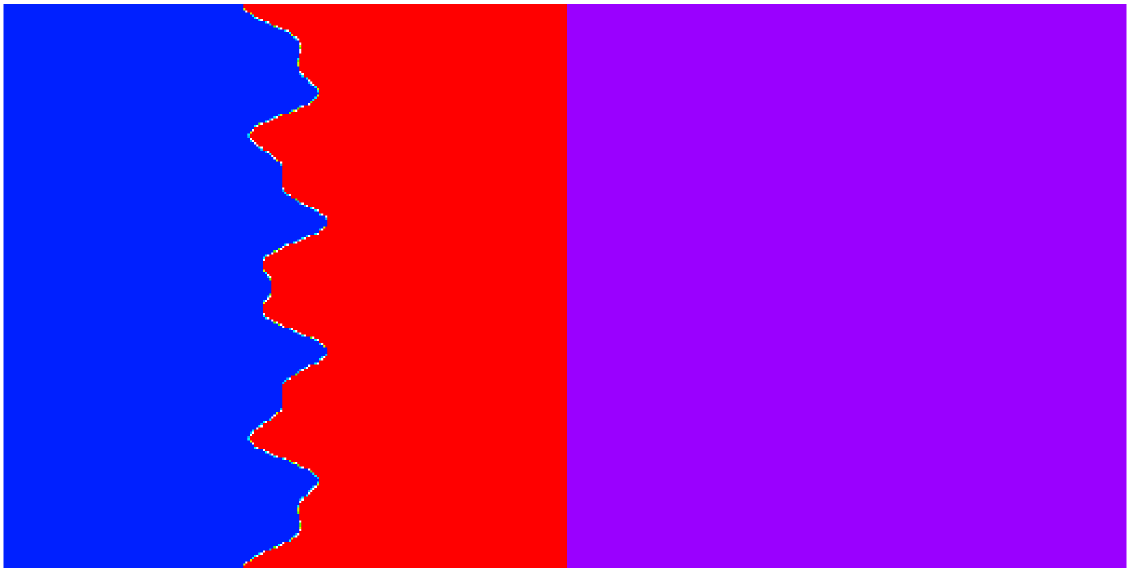

Figure 1. Initial mass density contours in RAGE runs. Red is 10 g/cm^3, blue is 1 g/cm^3, and purple is very low density. The flow will move to the right.

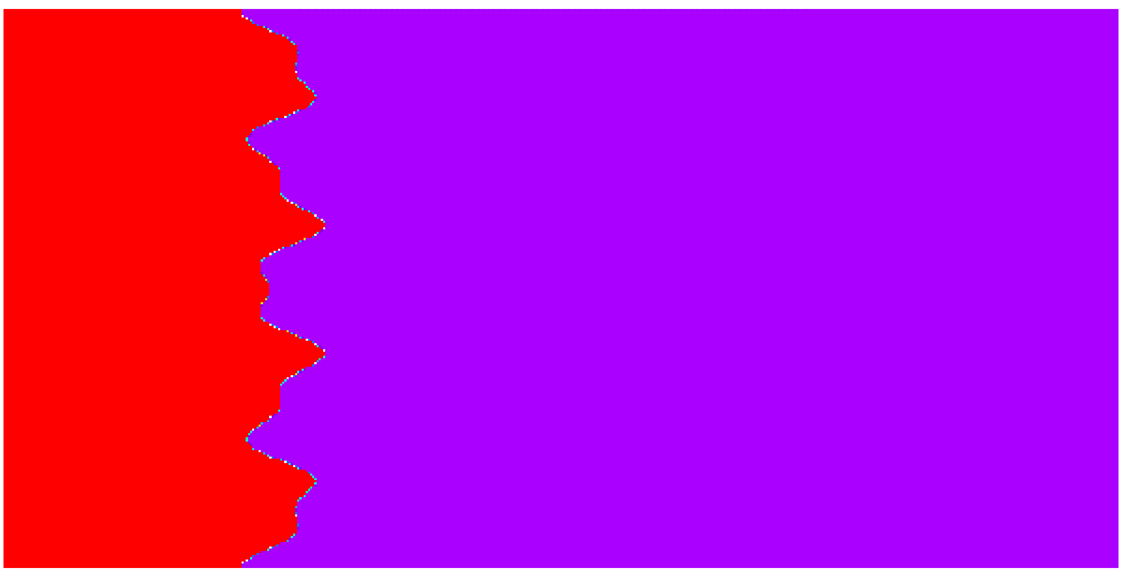

Figure 2. Initial material temperature contours in RAGE runs. Red is 1.5 keV, purple is 200 eV. The flow will move to the right.

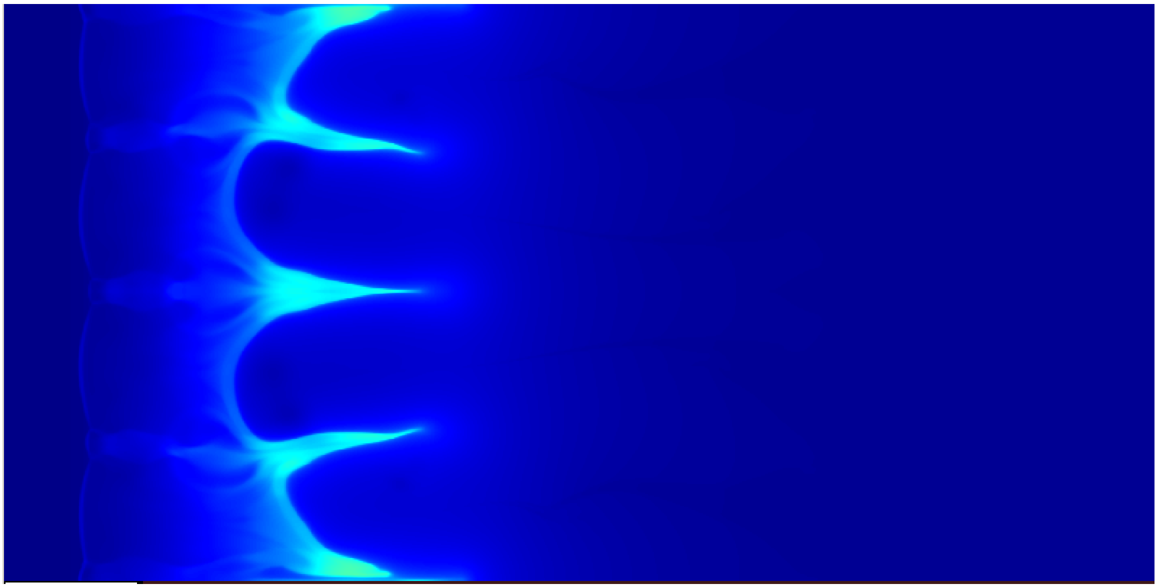

Figure 3. Density contour for 0.1 cm x 0.2 cm RAGE simulation at 22 ns. The hot region started on the right and the flow has moved to the left.

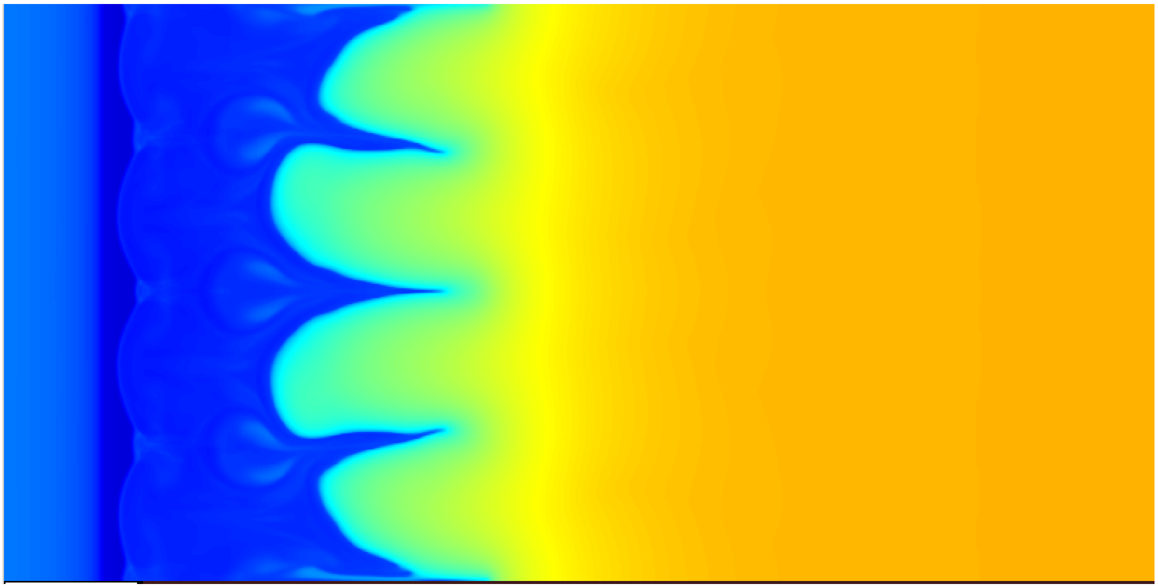

Figure 4. Material temperature contour for 0.1 cm x 0.2 cm RAGE simulation at 22 ns. The hot region started on the right and the flow has moved to the left.

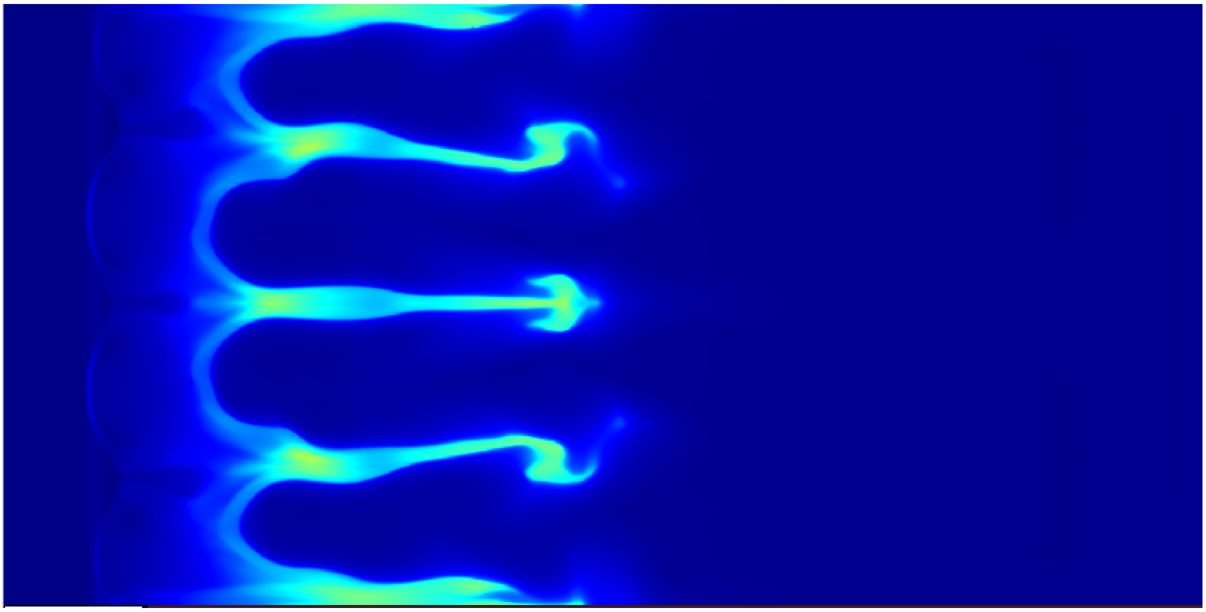

Figure 5. Density contour for 1.0 cm x 2.0 cm RAGE simulation at 220 ns. The hot region started on the right and the flow has moved to the left.

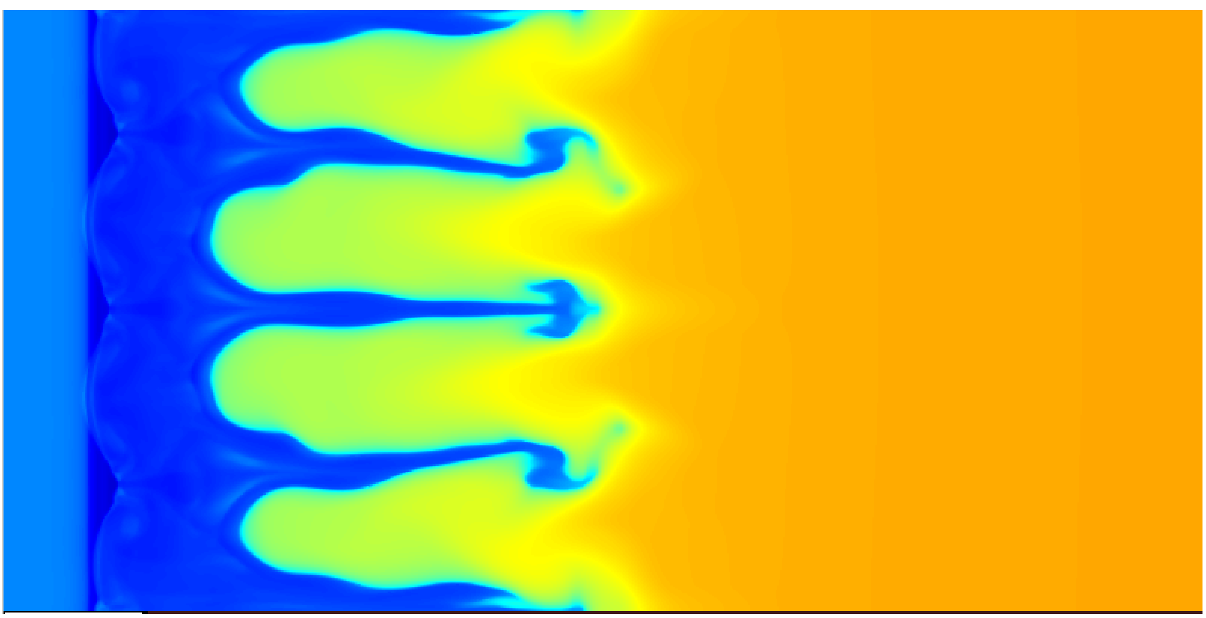

Figure 6. Material temperature contour for 1.0 cm x 2.0 cm RAGE simulation at 220 ns The hot region started on the right and the flow has moved to the left.

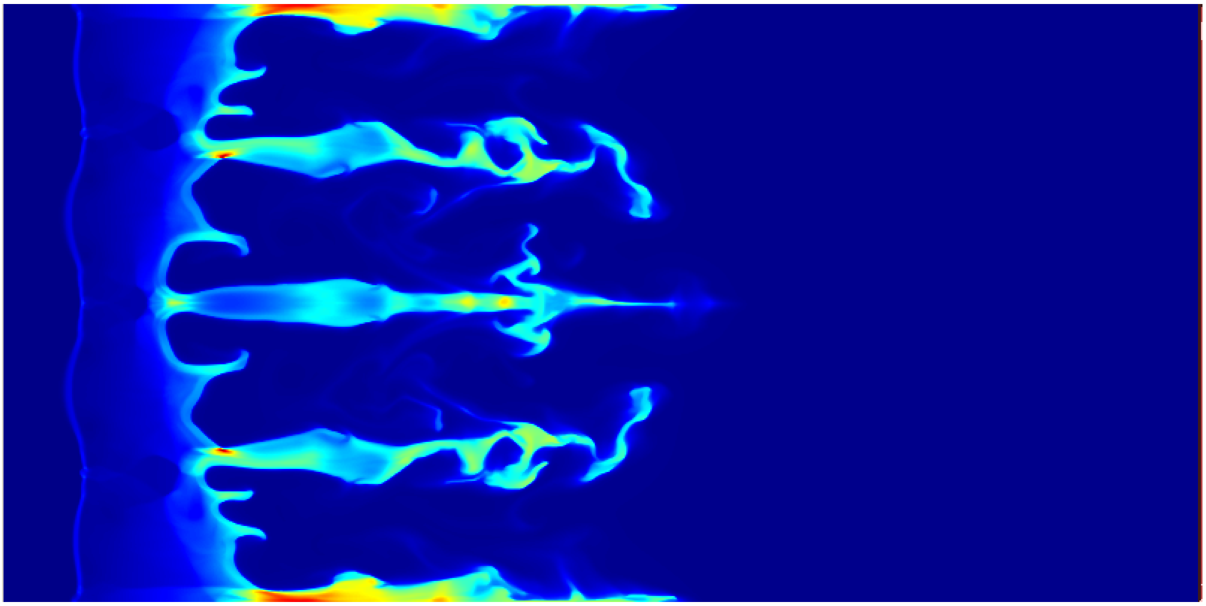

Figure 7. Density contour for 10 cm x 20 cm RAGE simulation at 2.2 μs. The hot region started on the right and the flow has moved to the left.

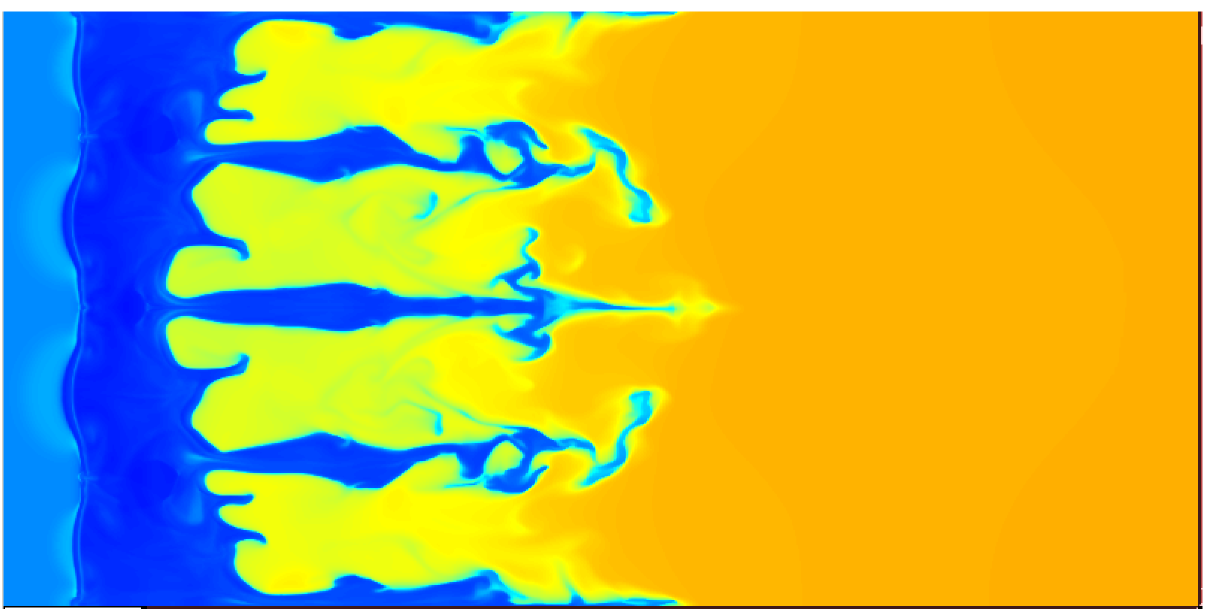

Figure 8. Material temperature contour for 10 cm x 20 cm RAGE simulation at 2.2 μs. The hot region started on the right and the flow has moved to the left.

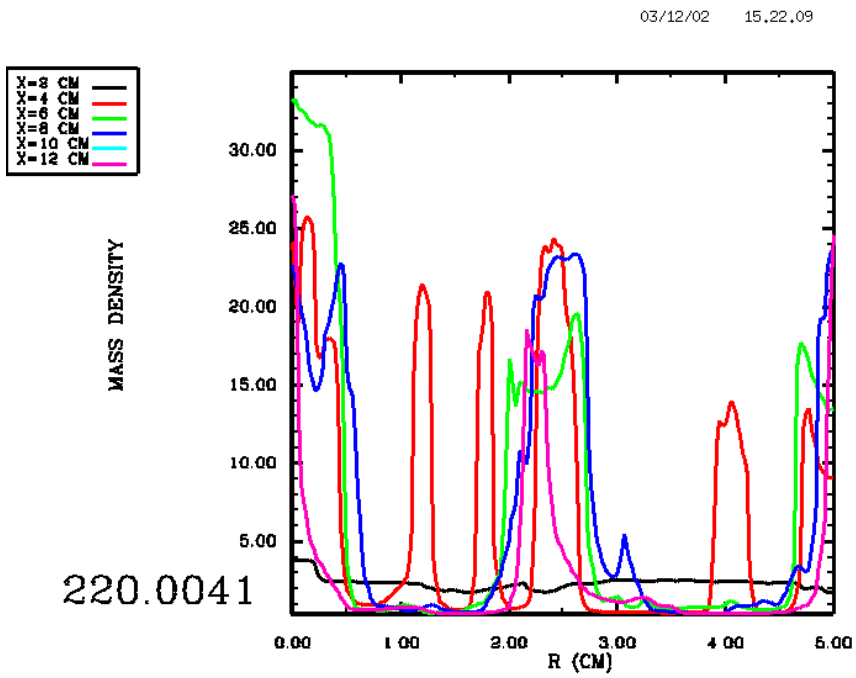

Figure 9. Density line-outs at various positions for 10 cm x 20 cm RAGE simulation at 2.2 μs. Line-outs are in a direction transverse to the direction of flow at 2, 4, 6, 8, 10 and 12 cm from the terminal end of the problem.

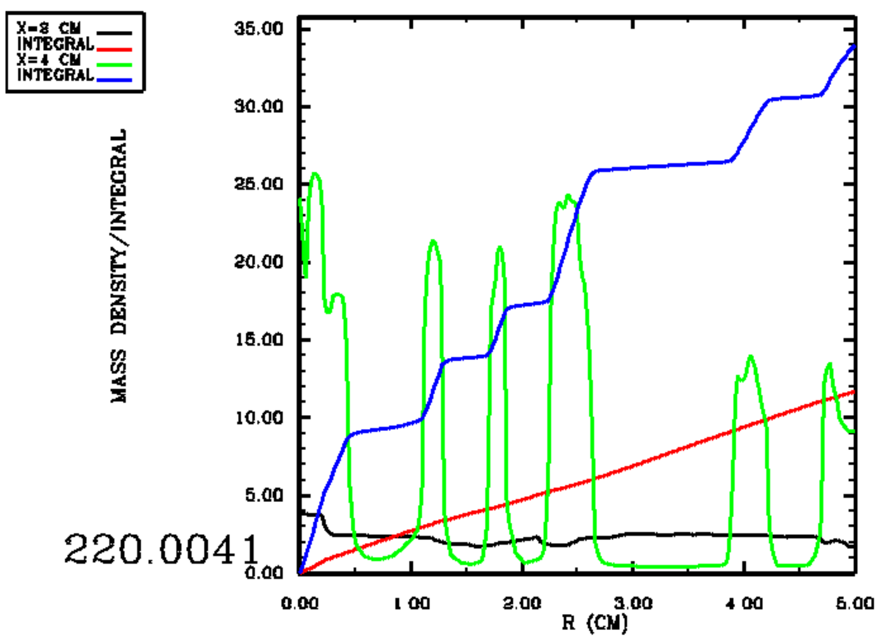

Figure 10. Density line-outs and integrals along those line-outs at various positions for 10 cm x 20 cm RAGE simulation at 2.2 μs. Line-outs are in a direction transverse to the direction of flow at 2 cm and 4 cm from the terminal end of the problem.

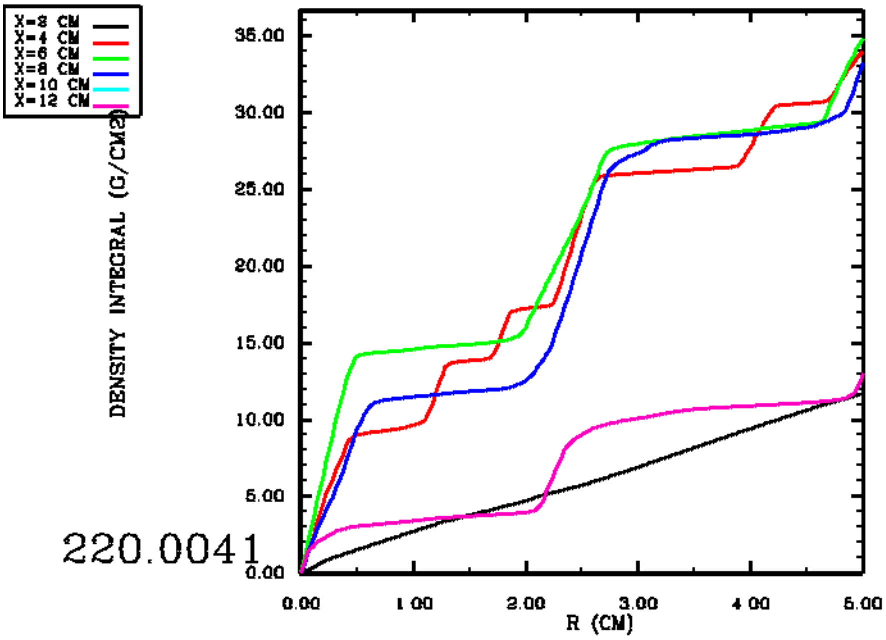

Figure 11. Integrals along density line-outs at various positions for 10 cm x 20 cm RAGE simulation at 2.2 μs. Line-outs are in a direction transverse to the direction of flow at 2, 4, 6, 8, 10 and 12 cm from the terminal end of the problem.

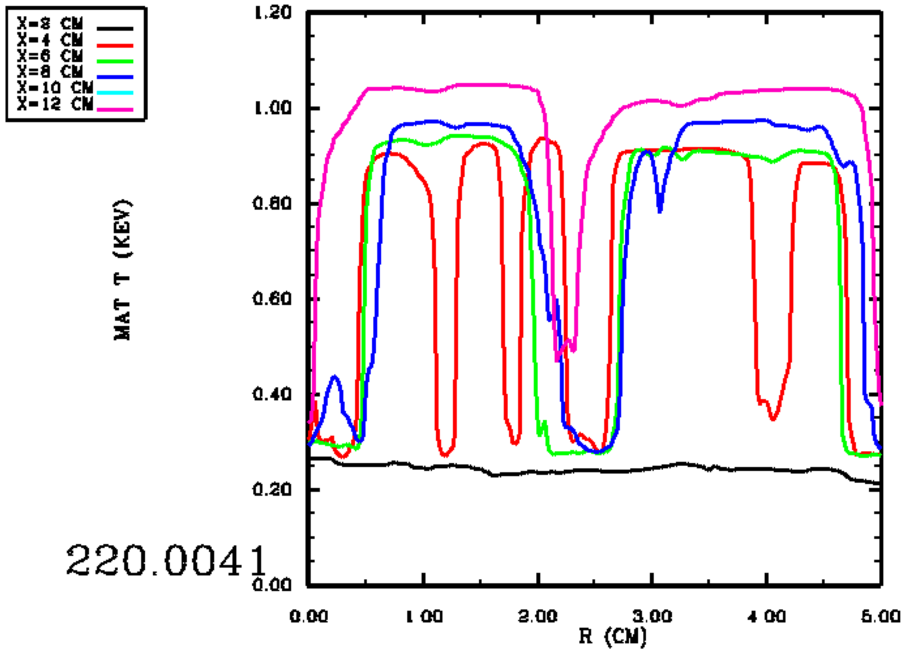

Figure 12. Material temperature line-outs at various positions for 10 cm x 20 cm RAGE simulation at 2.2 μs. Line-outs are in a direction transverse to the direction of flow at 2, 4, 6, 8, 10 and 12 cm from the terminal end of the problem.

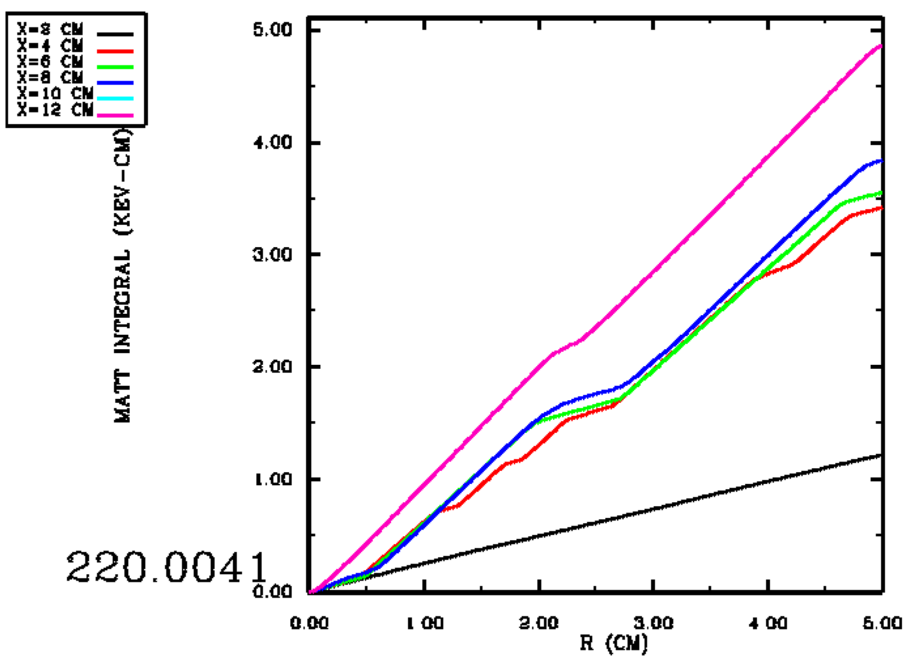

Figure 13. Integrals along material temperature line-outs at various positions for 10 cm x 20 cm RAGE simulation at 2.2 μs. Line-outs are in a direction transverse to the direction of flow at 2, 4, 6, 8, 10 and 12 cm from the terminal end of the problem.

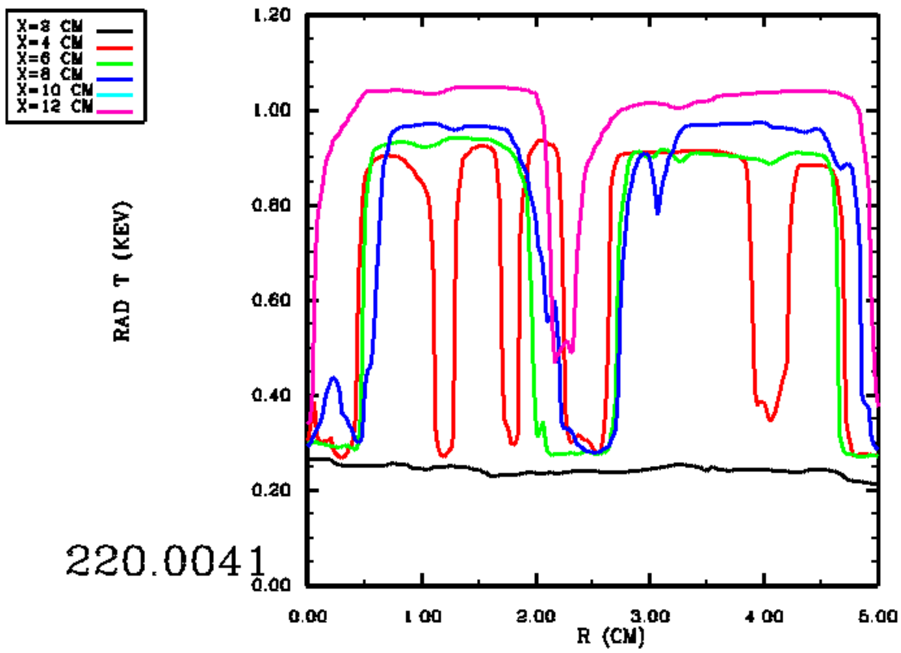

Figure 14. Radiation temperature line-outs at various positions for 10 cm x 20 cm RAGE simulation at 2.2 μs. Line-outs are in a direction transverse to the direction of flow at 2, 4, 6, 8, 10 and 12 cm from the terminal end of the problem.

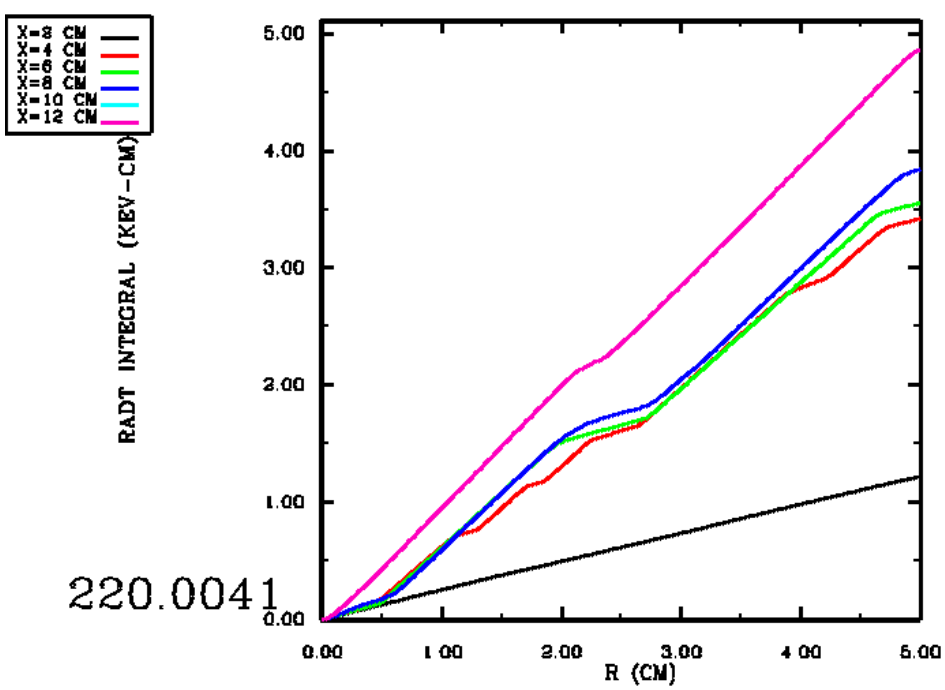

Figure 15. Integrals along radiation temperature line-outs at various positions for 10 cm x 20 cm RAGE simulation at 2.2 μs. Line-outs are in a direction transverse to the direction of flow at 2, 4, 6, 8, 10 and 12 cm from the terminal end of the problem.

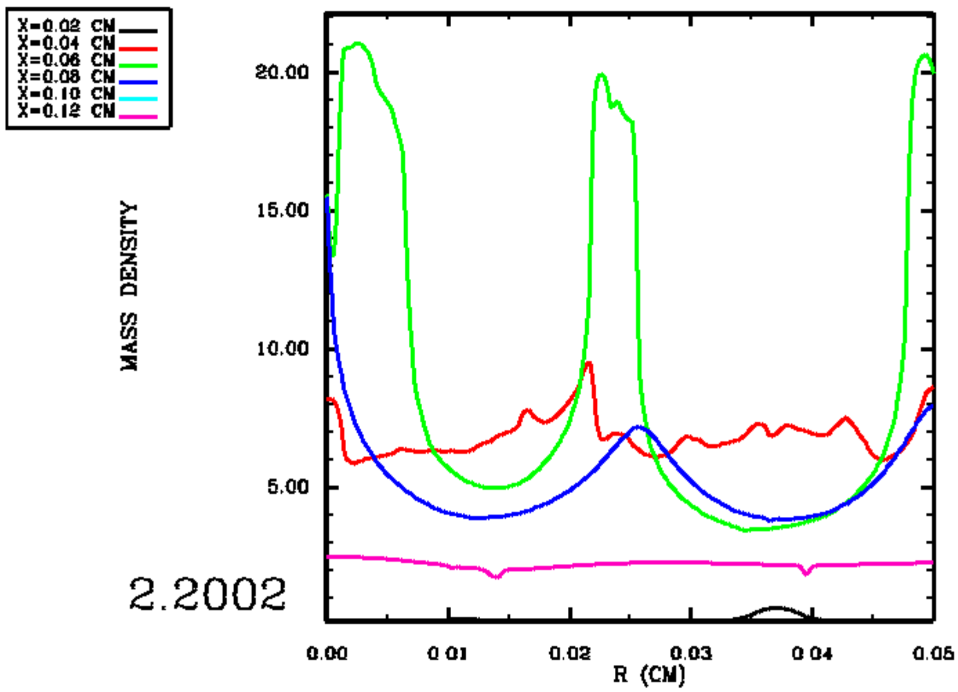

Figure 16. Density line-outs at various positions for 0.1 cm x 0.2 cm RAGE simulation at 22 ns. Line-outs are in a direction transverse to the direction of flow at 0.02, 0.04, 0.06, 0.08, 0.10 and 0.12 cm from the terminal end of the problem.

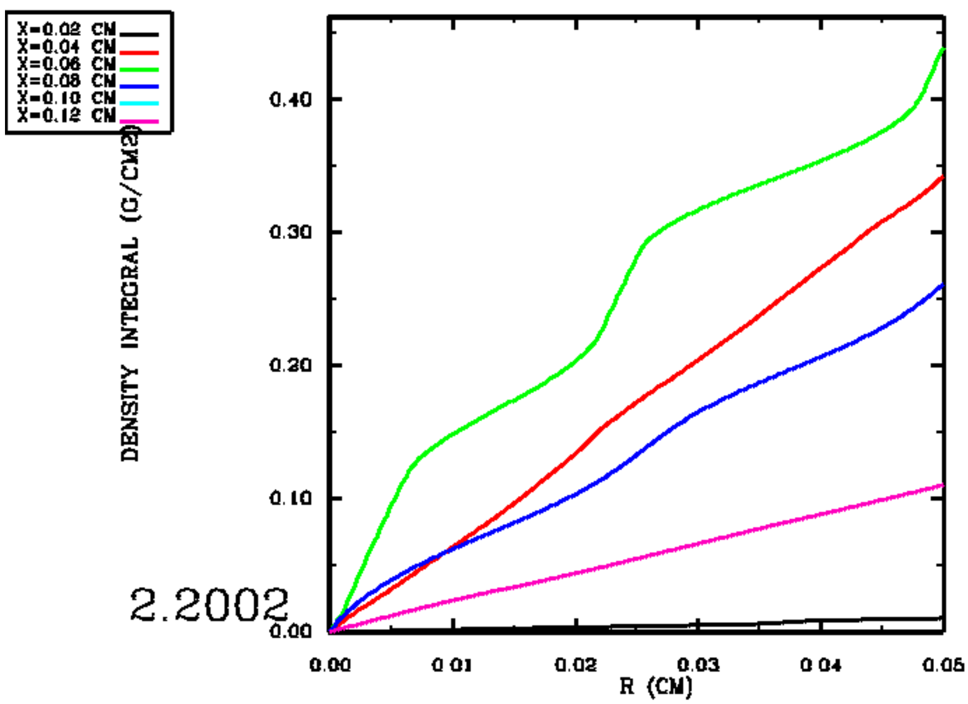

Figure 17. Integrals along material density line-outs at various positions for 0.1 cm x 0.2 cm RAGE simulation at 22 ns. Line-outs are in a direction transverse to the direction of flow at 0.02, 0.04, 0.06, 0.08, 0.10 and 0.12 cm from the terminal end of the problem.

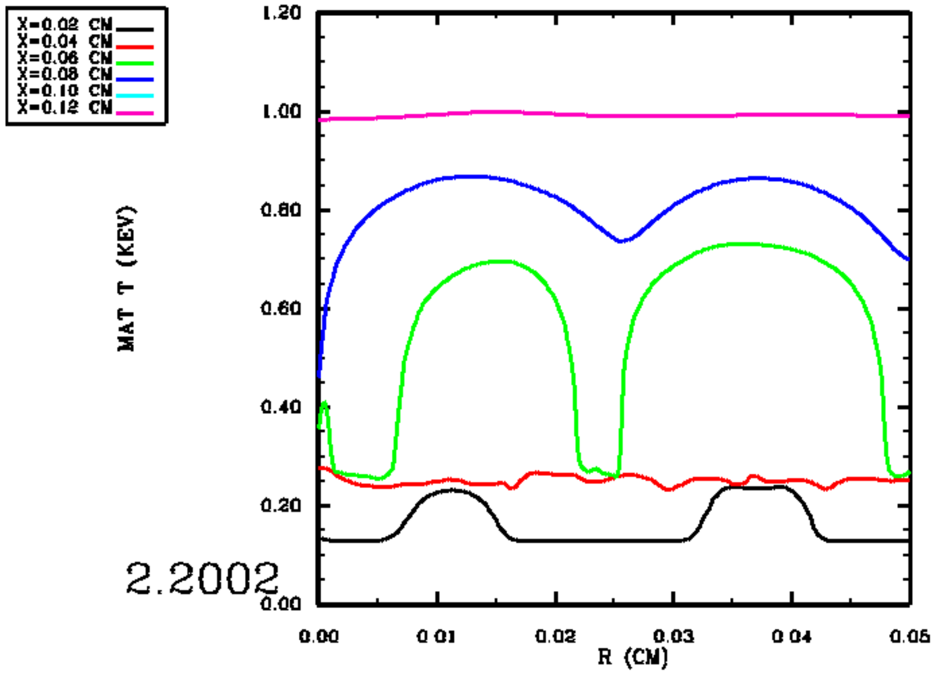

Figure 18. Material temperature line-outs at various positions for 0.1 cm x 0.2 cm RAGE simulation at 22 ns. Line-outs are in a direction transverse to the direction of flow at 0.02, 0.04, 0.06, 0.08, 0.10 and 0.12 cm from the terminal end of the problem.

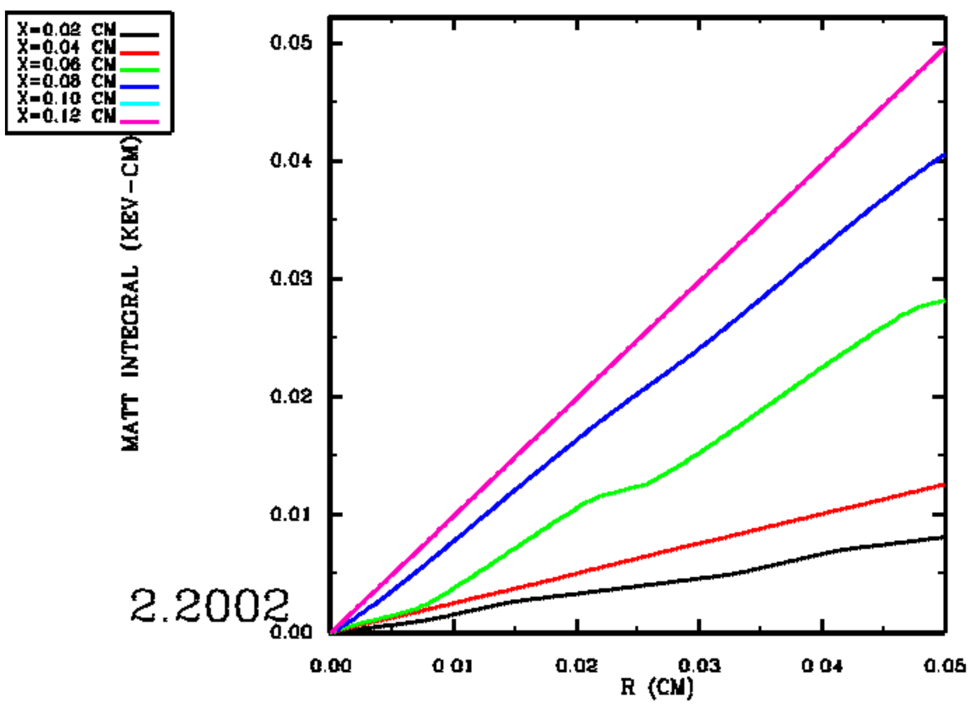

Figure 19. Integrals along material temperature line-outs at various positions for 0.1 cm x 0.2 cm RAGE simulation at 22 ns. Line-outs are in a direction transverse to the direction of flow at 0.02, 0.04, 0.06, 0.08, 0.10 and 0.12 cm from the terminal end of the problem.

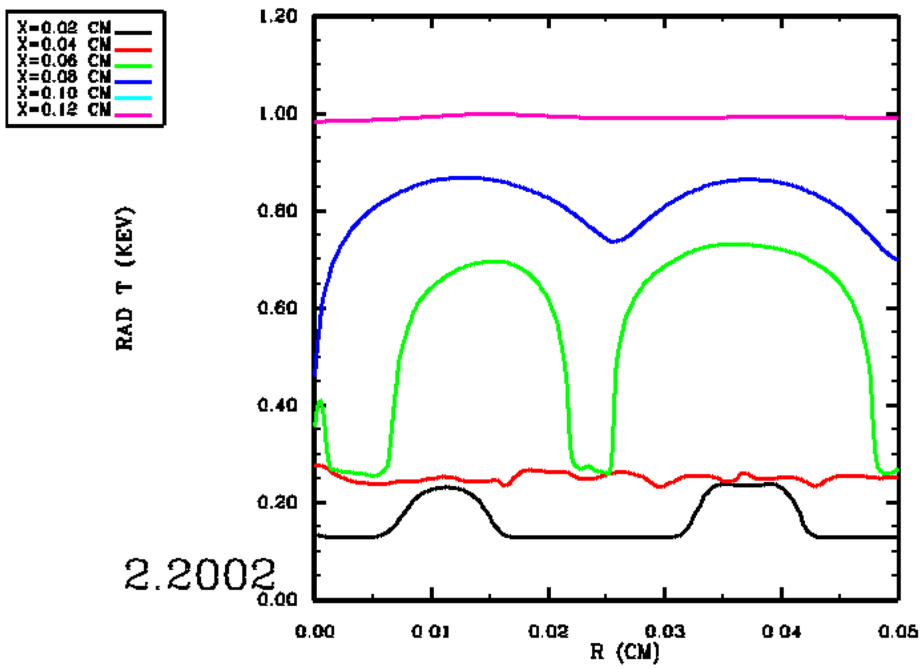

Figure 20. Radiation temperature line-outs at various positions for 0.1 cm x 0.2 cm RAGE simulation at 22 ns. Line-outs are in a direction transverse to the direction of flow at 0.02, 0.04, 0.06, 0.08, 0.10 and 0.12 cm from the terminal end of the problem.

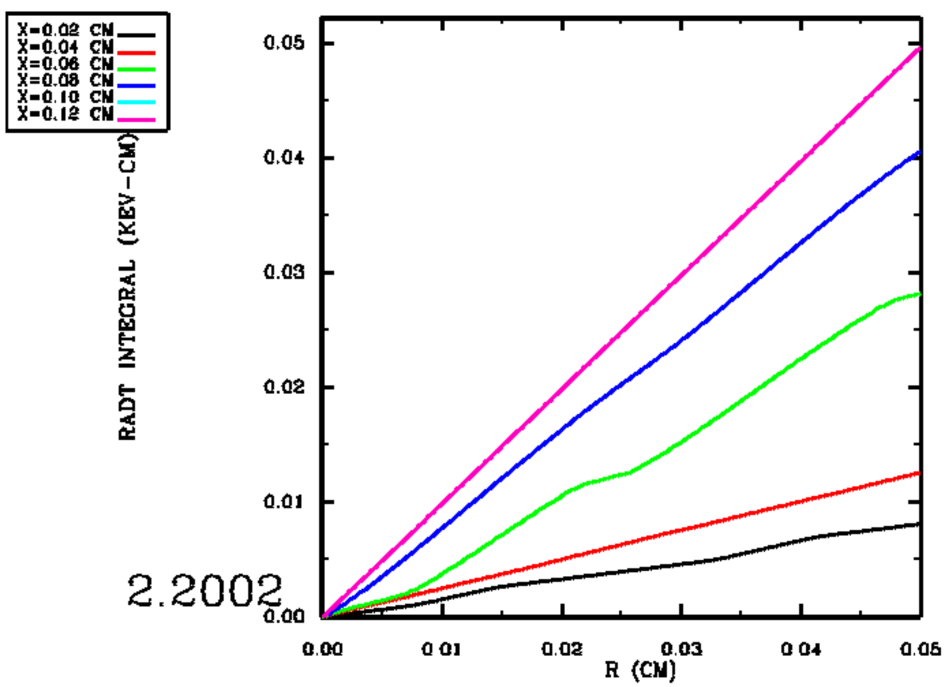

Figure 21. Integrals along radiation temperature line-outs at various positions for 0.1 cm x 0.2 cm RAGE simulation at 22 ns. Line-outs are in a direction transverse to the direction of flow at 0.02, 0.04, 0.06, 0.08, 0.10 and 0.12 cm from the terminal end of the problem.

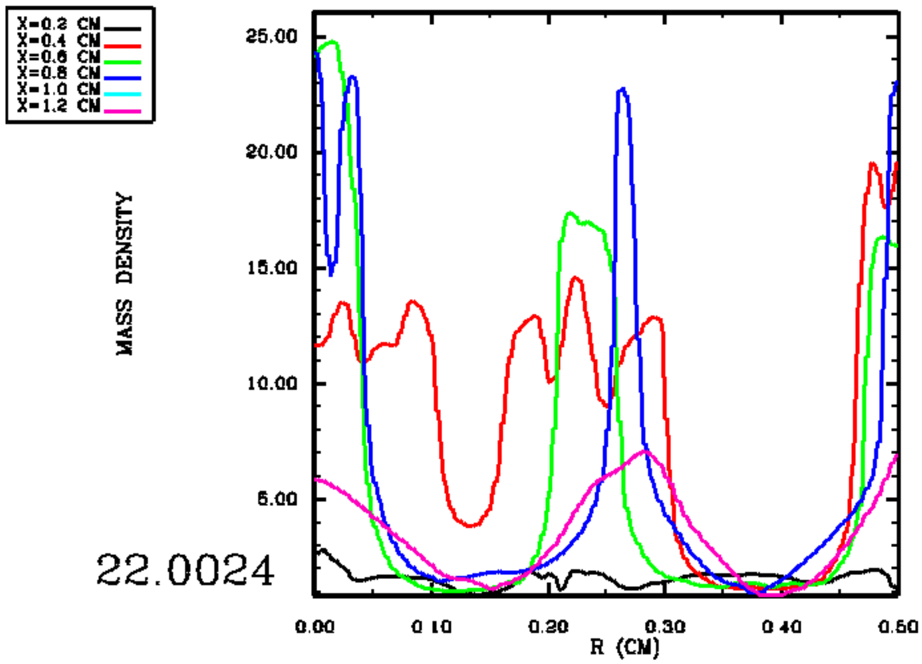

Figure 22. Density line-outs at various positions for 1.0 cm x 2.0 cm RAGE simulation at 220 ns. Line-outs are in a direction transverse to the direction of flow at 0.2, 0.4, 0.6, 0.8, 1.0 and 1.2 cm from the terminal end of the problem.

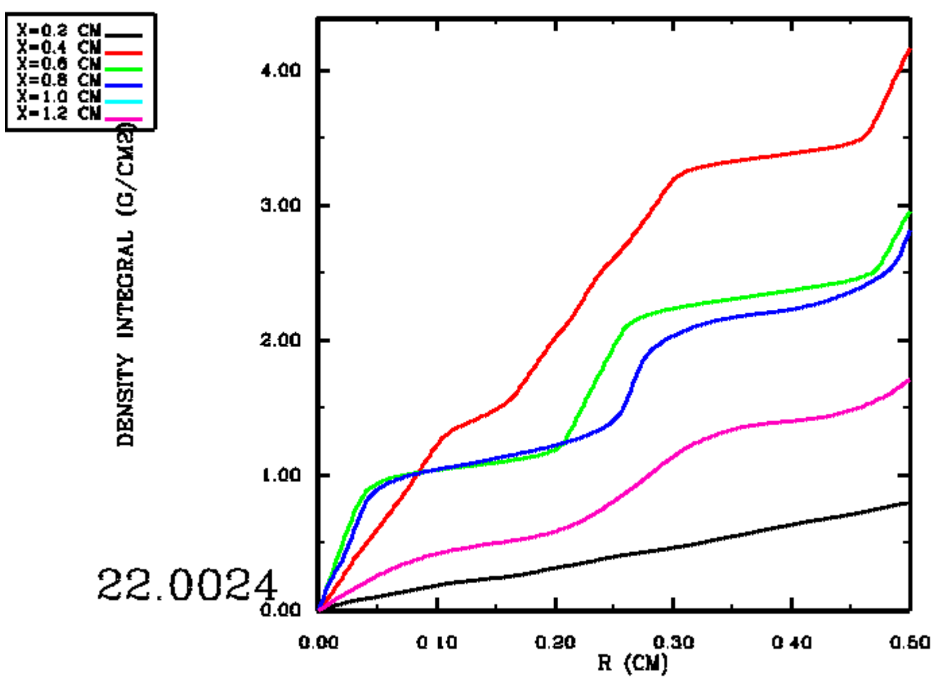

Figure 23. Integrals along density line-outs at various positions for 0.1 cm x 0.2 cm RAGE simulation at 220 ns. Line-outs are in a direction transverse to the direction of flow at 0.02, 0.04, 0.06, 0.08, 0.10 and 0.12 cm from the terminal end of the problem.

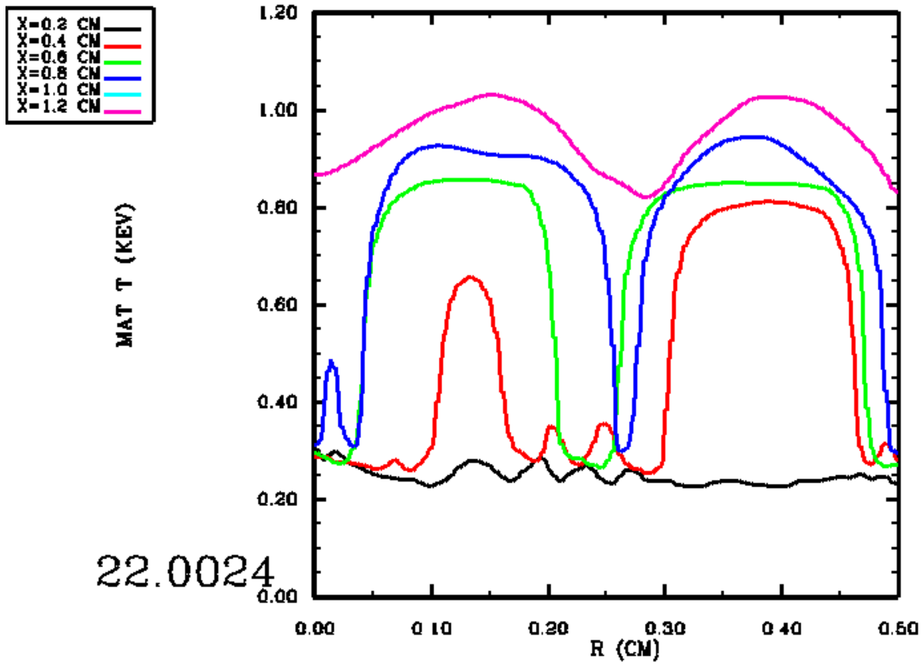

Figure 24. Material temperature line-outs at various positions for 1.0 cm x 2.0 cm RAGE simulation at 220 ns. Line-outs are in a direction transverse to the direction of flow at 0.2, 0.4, 0.6, 0.8, 1.0 and 1.2 cm from the terminal end of the problem.

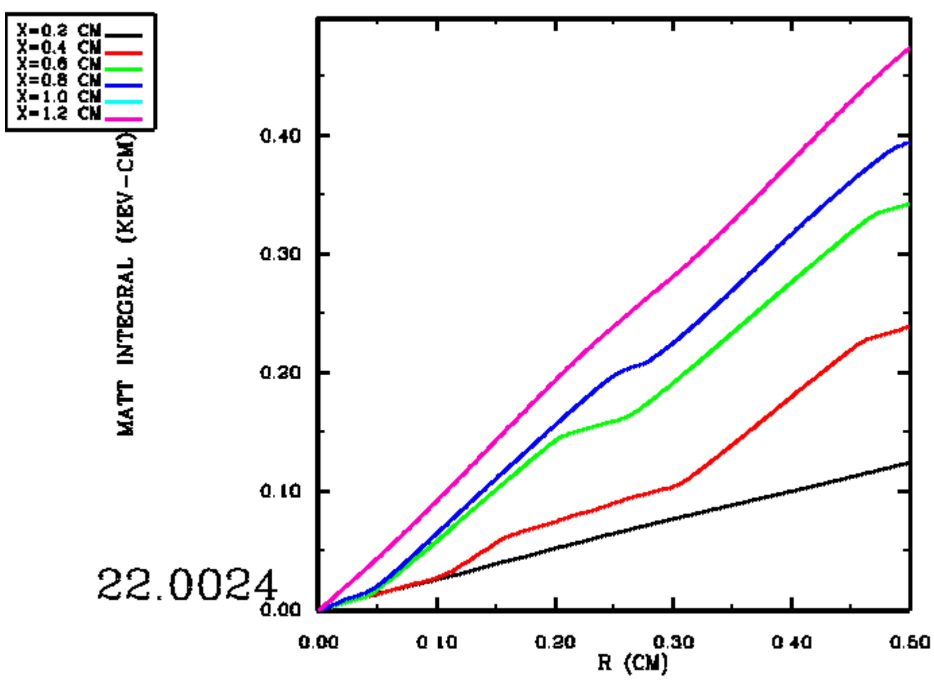

Figure 25. Integrals along material temperature line-outs at various positions for 0.1 cm x 0.2 cm RAGE simulation at 220 ns. Line-outs are in a direction transverse to the direction of flow at 0.02, 0.04, 0.06, 0.08, 0.10 and 0.12 cm from the terminal end of the problem.

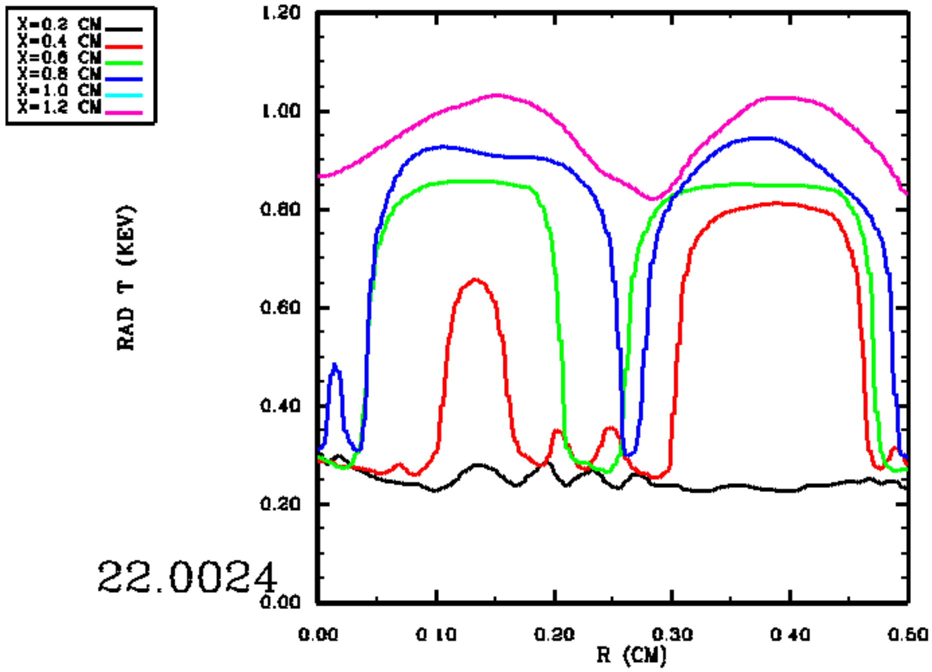

Figure 26. Radiation temperature line-outs at various positions for 1.0 cm x 2.0 cm RAGE simulation at 220 ns. Line-outs are in a direction transverse to the direction of flow at 0.2, 0.4, 0.6, 0.8, 1.0 and 1.2 cm from the terminal end of the problem.

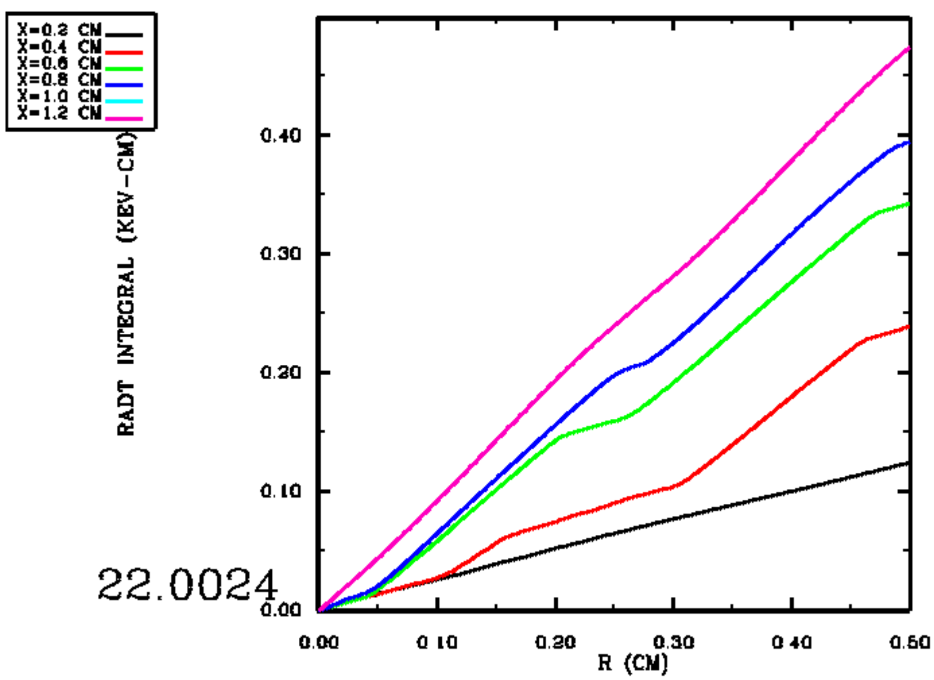

Figure 27. Integrals along radiation temperature line-outs at various positions for 0.1 cm x 0.2 cm RAGE simulation at 220 ns. Line-outs are in a direction transverse to the direction of flow at 0.02, 0.04, 0.06, 0.08, 0.10 and 0.12 cm from the terminal end of the problem.