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Characteristic parameters of diffusive supersonic radiation transport in low density materials

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Diffusive heat waves play an important role in radiation hydrodynamics. In low density material, it may be possible that the radiative energy flux dominates the material energy flux and thus energy flow can be determined. In this paper by means of a simple algebraic method, the expressions characterizing the condition of diffusion approximation and supersonic transport of heat wave are found. In this case, the ratio of the radiative energy flux to the material energy flux is directly proportional to the product of Mach number M multiplied by optical depth τ. And it may also be expressed by radiation temperature heating material. The material density and length may be determined in order to achieve above-mentioned conditions when the driven temperature and duration are given.

Keywords: radiation transport, Mach number, optical depth, critical radiation temperature

PACC: 5250J, 4770M, 4440, 5225F

1. Introduction

The investigation of the propagation of heat waves generated in low density matters by an intensive soft x-ray flux is important for many fields such as inertial confinement fusion (ICF) and astrophysics.[1−9] An intense radiation flux rapidly heats the low density material which has a small opacity to incident radiation. Radiation passes through the heated material and is absorbed at the boundary of the cold material, thus creating a steep heat front. The heat front propagates supersonically or it is preceded by a shock. The propagation of heat front through material supersonically may eventually relax to a subsonic front.

By lowering the density of the x-ray heated material, it is possible to extend the pure nonablative period into the nanosecond range and observe the supersonic heat wave driven by x-ray radiation.[2] Additionally, by using low density material, usually called foam, it is likely that the radiative energy flux dominates the material energy flux and thus energy flow can be determined. The ratio of these two terms is[4]

$$\gamma = \frac{\text{radiitive energy flux}}{\text{material energy flux}} = \frac{F_{\rm R}}{F_{\rm M}} = \frac{\sigma T^4}{\rho\varepsilon c_{\rm s}}, \qquad (1)$$

where σ is the Stefan–Boltzmann constant, T is the temperature, ε is the specific internal energy, ρ is the mass density, and $c_{\rm s}$ is the sound speed.

Mashak first considered one-dimensional radiative heating of the cold material under the condition of local thermodynamic equilibrium (LTE) between radiation and material.[10] Zel'dolvich and Raizer[11] well described the relevant energy balance and radiation transport equations in their textbook. Recently radiative heating has been observed in the laboratory by an ionization wave in an optically thin sample[1,5,6] or by thermal emission in an optical thick sample.[2−4] The physics of radiation transport in hot plasmas has been detailedly reviewed in the tutorial paper.[12]

The radiation temperature, which characterizes the radiation flux, is a key parameter in the indirect driven ICF. Neutron yield is a primary parameter in the experiments of exploding pusher mode directly driven. When the supersonic heat wave transports along foam, what are its characteristic parameters? And what relations are there between γ and these characteristic parameters?

Propagation of diffusive supersonic wave in a radiatively heated foam is reviewed in Section 2, and the expression of γ is derived by using analytic solutions for supersonic diffusive waves with material properties varying as ρ, T power laws. In Section 3, the transition times for plastic, aluminium and gold material

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are calculated and the time evolution of the heating process is analysed. The relation between γ and the critical temperature T_c is given in Section 4. The condition on the propagation of the diffusively supersonic wave in material is analysed. A summary is given in Section 5.

2. Mach number and optical depth

The physical complexity of radiation transport within a plasma and the numerical difficulties in solving the transport equation, both stem from the fact that the absorption and emission coefficients not only determine the radiation field, but also (usually) to a significant extent are determined by it. For instance, the absorption coefficient at a given frequency approximately equals to the population density of atomic states multiplied the absorption cross section , these states absorb photons of that frequency. However, this population density is influenced by radiative processes such as photo-excitation and photonionization. In general, therefore, iteration is required between the formal solution of the transport equation and a set of atomic rate equation (which must include the radiation field and all significant radiative processes). In some instances, prevailing plasma conditions such as an optically thick plasma, may result in a much simpler physical picture as well as a much less daunting numerical challenge of transport equation.[12]

The basic equation for supersonic, diffusion radiative transport in one dimension is[13]

$$\rho\frac{\partial\varepsilon}{\partial t}=\frac{4}{3}\frac{\partial}{\partial x}\frac{1}{\kappa\rho}\frac{\partial(\sigma T^4)}{\partial x}, \tag{2}$$

where ε is the internal energy per unit mass, κ is the Rosseland mean opacity, t is time, and x is the spatial coordinate, ε and κ are specified functions of ρ and T for given materials and their expressions look like[14]

$$\varepsilon=\varepsilon_0 T^m, \tag{3}$$

$$\kappa=\kappa_0 T^{-n}\rho^b, \tag{4}$$

where ε_0 and κ_0 are constants. The actual expression of ε is $\sim T^m\rho^{-\beta}$. However, in most cases of interest $\beta\ll 1$ and here we take $\beta=0$.

If the velocity of heat front is much greater than the speed of sound in the heated materials, ρ is considered as a constant since hydrodynamic motion is too slow to give rise to density changes. Typical boundary conditions of for the solution of Eq.(2) are either a known surface temperature or incident radiation flux as a function of time. If the material has finite thickness, the temperature or incident flux on both boundaries must be determined. However, following Hammer and Rosen, we will only consider the case of a semi-infinite slab of materials whose surface conditions are given.[11] A solution Eq.(2) for the position of heat front is[4]

$$x_{\rm F}=\sqrt{\frac{32}{3(n+4-1.5m)}\frac{\sigma T^4 t}{\kappa\rho^2\varepsilon}}. \tag{5}$$

Which shows the characteristic $t^{0.5}$ dependence of diffusion wave, when the boundary temperature is kept at a constant temperature.

Using Eq.(5), we can express the average velocity of heat front as

$$u_{\rm h}=\frac{x_{\rm F}}{t}=\frac{1}{\alpha x_{\rm F}}\frac{\sigma T^4}{\kappa\rho^2\varepsilon}, \tag{6}$$

where

$$\alpha=\frac{3(n+4-1.5m)}{32}. \tag{7}$$

For most materials,[15,16] $1<m<1.5, 1.5<n<2.5$, and then $0.3<\alpha<0.5$. The speed of sound is assumed to be[14]

$$c_{\rm s}=\sqrt{\varepsilon}. \tag{8}$$

The Mach number is defined as the ratio of the heat front velocity to the heated material sound speed,[4] i.e.

$$M=\frac{u_{\rm h}}{c_{\rm s}}=\frac{1}{\alpha x_{\rm F}}\frac{\sigma T^4}{\kappa\rho^2\varepsilon^{1.5}}. \tag{9}$$

Define the optical depth

$$\tau=\int\kappa\rho{\rm d}x=\kappa\rho x_{\rm F}=x_{\rm F}/l_{\rm R}, \tag{10}$$

where $l_{\rm R}=\rho\kappa^{-1}$ is Rosseland mean free path. τ is an integral quantity of the opacity over distance and is a measure of the diffusivity of the medium. At roughly one optical depth, the photons begin to thermalize and the diffusive approximation begins to be applicable. Because laboratory research in radiation transport is limited by the energy available to drive a sample, it is difficult to make the optical depth to be very high. Back *et al*[4] reached $\tau\sim 4$ in the experiments on the Omega facility.

Inserting Eqs.(9) and (10) into Eq.(1), we obtain

$$\gamma=\frac{\sigma T^4}{\rho\varepsilon c_{\rm s}}=\frac{3(n+4-1.5m)}{32}\frac{u_{\rm h}}{c_{\rm s}}\frac{x_{\rm F}}{l_{\rm R}}=\alpha M\tau. \tag{11}$$

The diffusion approximation requires that plasma is optical thick, i.e., $\tau > 1$, and if $M > 1/\alpha, \gamma > 1$, and accordingly the radiative energy flux is dominant in the balance of energy flow.

The heat wave extends beyond the hydrodynamic motion that takes the form of a weak, ablative compression wave propagating behind the radiation heat front. The weak density disturbances seen at the position of the front can be understood from classical radiation hydrodynamics. For simplicity, if we assume isothermal equilibrium in the downstream plasma then the density jump should be given approximately by[1]

$$\rho_1 \approx (1 + M^{-2})\rho_0. \tag{12}$$

From Eq.(12), when $M > 3$, the hydrodynamic density perturbations at the heat front remain less than 0.1 and we consider the radiation transport supersonic when this condition is met. Therefore, the conditions of a diffusive supersonic wave in a heated material driven by radiation are

$$M > 3 \text{ and } \tau > 1. \tag{13}$$

When the conditions of Eq.(13) are met, using Eqs.(12) and (7) since $0.3 < \alpha < 0.5$ we obtain $\gamma > 1$. Herein, the optical depth τ and Mach number M may characterize supersonic propagation of radiation in a diffusive low density material. After M and τ are measured, γ can easily be calculated with Eq.(12). Therefore, we may think that τ and M are two characteristic parameters of diffusive supersonic wave in a heated low density material. Besides γ, the ratio of radiative energy density to material energy density may also be expressed with M and τ as

$$\delta = \frac{\text{raditive energy density}}{\text{material energy density}} = \frac{E_{\mathrm{R}}}{E_{\mathrm{M}}} = \frac{\sigma T^4/c}{\rho\varepsilon} = \frac{\sigma T^4}{\rho\varepsilon c_{\mathrm{s}}}\frac{c_{\mathrm{s}}}{c} = \gamma\frac{c_{\mathrm{s}}}{c}, \tag{14}$$

where c is the speed of light. The speed of sound is much smaller than the speed of light, $\delta << \gamma$. For the present condition in most of laboratories, the radiation temperature driving foam sample ranges from 100 eV to 200 eV. Assuming a plasma temperature equal to the maximum x-ray driven temperature and ignoring reductions due to nonideal gas behaviour, the sound speed is about 10^7 cm/s, from Eq.(14) we obtain

$$\delta \approx 3 \times 10^{-4}\gamma = 3 \times 10^{-4}\alpha M\tau. \tag{15}$$

Using a simple approximate method, Hammer and Rosen[13] found an approximate solution of Eq.(2) for the position of the heat front where

$$x_{\mathrm{F}} = \sqrt{\frac{8}{3}\frac{\sigma T^4}{\kappa\rho^2\varepsilon}}t. \tag{16}$$

According to Eq.(16), we have

$$\gamma = \frac{3}{8}M\tau = 0.375M\tau. \tag{17}$$

Moreover, Hammer and Rosen[13] have also derived a general solution of Eq.(2), which yields Eq.(5) under the condition of the constant temperature on the boundary.

3. The heating process of radiation in material

From Eqs.(3) and (4), we can express the mean free path l_{R} with ε and ρ in the form of a power law

$$l_{\mathrm{R}} = (\kappa\rho)^{-1} = l_0\varepsilon^s/\rho^r, \tag{18}$$

where $s = n/m, r = b + 1, l_0 = [\kappa_0\varepsilon_0^{n/m}]^{-1}$. Piriz and Tomasel[14] developed a simple model which gave a qualitative picture of the process taking place when a cold medium is heated by the thermal radiation. According to Piriz and Tomasel, the heat wave may be supersonic or ablative depending on the time evolution of the incident x-ray flux. When an intense thermal flux heats a cold material, it may give rise to four possible processes, which include a supersonic heat and ablative heat wave (SHW-NLTE and AHW-NLTE) during the nonlocal thermodynamic equilibrium (NLTE) phase and a supersonic heat and ablative heat wave (SHW-LTE and AHW-LTE) during LTE phase, and then, several of these processes may be determined by the driven temperature T, its temporal evolution, and the density ρ_0 and the properties of the materials. They derived the critical value T_{c} of

the radiation temperature and the critical time value τ_c. Assuming a self-regulating mechanism for the radiation optical depth, they divided the space (T,t) into four regions that correspond to four possible regimes of heat wave presented above. The particular case in which the heated material is aluminium is considered as an example. The corresponding diagram in the space (T,t) is shown in Fig.1.

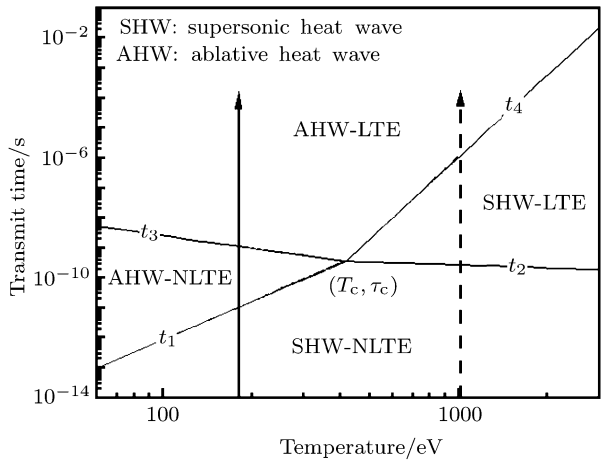


Fig.1. Times for t_1 and t_4 for the transition from a SHW to an AHW for NLTE and LTE conditions, respectively, and times t_2 and t_3 for the equilibrium in the supersonic and in the ablative regimes, respectively.

It is noted that there exists a critical radiation temperature T_c. At that point, the transition from a SHW to an AHW, or vice versa, occurs simultaneously with the achievement of equilibrium:[14]

$$T_c = (\varepsilon_0^{1.5}\rho_0/\sigma)^{\frac{2}{8-3m}} \tag{19}$$

$$\tau_c = l_0\left(\frac{\varepsilon_0^{4/m}}{\sigma}\right)^{\frac{m(2s-1)}{8-3m}} \rho_0^{\frac{m(3r+2s-1)-8r}{8-3m}}. \tag{20}$$

The expressions for the transition times are given[14]

$$t_1 = \tau_c(T/T_c)^{\frac{4(2s-1)}{3}}, \tag{21}$$

$$t_2 = \tau_c(T/T_c)^{m(s+1)-4}, \tag{22}$$

$$t_3 = \tau_c(T/T_c)^{-\frac{(8-3m)(r+s)-4(2s-1)}{3}}, \tag{23}$$

$$t_4 = \tau_c(T/T_c)^{\frac{8[m(s-2)+4]}{3m}}. \tag{24}$$

The diagram shown in Fig. 1 denotes the possible evolution of the heating process depending on the value of the radiation temperature. If $T < T_c$, the SHW-LTE does not happen and the AHW-LTE is achieved after a phase where the AHW-NLTE takes place. This heating process was studied in detail by Kaiser *et al*,[17] who also obtained the transition times t_1 and t_3 by using the method of self-similar solutions. When a material is heated, it becomes more transparent and the driving radiation can penetrate more deeply, and creates a SHW-NLTE. There are three different phases in this process with time evolution. At first, it proceeds at constant density, this phase is called the SHW-NLTE, since the wave front progresses faster than sound and the material is not in equilibrium with radiation. In time, due to the increasing mass of heated material, the heat wave slows down, and then is overtaken by a shock wave when $t = t_1$, thus becomes the ablative type, called the AHW-NLTE. When equilibrium between the radiation and the heated matter is achieved, the phase evolves into AHW-NLTE at $t = t_3$. This heating process evolves along solid line arrow in Fig.1. If $T > T_c$, the intermediate phase is a SHW-LTE and the AHW-NLTE never occurs. At $t = t_2$, SHW-NLTE develops into SHW-LTE, and AHW-LTE can also be reached provided that sufficient time is available, at $t = t_4$. This case changes along the dashed line arrow in Fig.1.

For the purpose of demonstrating the possible time evolution of the heating process, the particular cases in which the heated materials are plastic, aluminium and gold are considered as the representative of low, medium and high Z materials respectively. The expressions of equation of state and opacity are in the following form of a power law:

$$\varepsilon_{CH} = 8.6\times10^{11}T, \tag{25}$$

$$l_{CH} = 1.811\times10^{-37}\varepsilon^{2.429}\rho^{-1.542}, \tag{26}$$

$$\varepsilon_{Al} = 3.6\times10^{11}T^{1.2}, \tag{27}$$

$$l_{Al} = 8.0\times10^{-33}\varepsilon^{2.0833}\rho^{-1.5}, \tag{28}$$

$$\varepsilon_{Au} = 1.85\times10^{10}T^{1.5}, \tag{29}$$

$$l_{Au} = 7.8\times10^{-17}\varepsilon^{1.0}\rho^{-1.2}. \tag{30}$$

In these expressions, ε is in erg/g, l is in cm, T is in eV, ρ in g/cm^3. The subscripts CH, Al and Au in Eqs.(25)–(30) indicate plastic, aluminium and gold respectively. Equations (25) and (26) are obtained by means of the average atom model.[16] Equations (27) and (28) are from Ref.[14]. Equations (29) and (30) are taken from Refs.[18] and [13] respectively. Substituting Eqs.(25)–(30) into Eqs.(19)–(24), we get the critical temperature T_c and time τ_c, and transition times, t_1 to t_4.

For plastic,

$$T_{\rm c} = 228.8\,({\rm eV}), \quad \tau_{\rm c} = 6.71\times10^{-10}\,({\rm s}), \quad t_1 = \tau_{\rm c}(T/T_{\rm c})^{5.414}, \quad t_2 = \tau_{\rm c}(T/T_{\rm c})^{-0.5712},$$
$$t_3 = \tau_{\rm c}(T/T_{\rm c})^{-1.926}, \quad t_4 = \tau_{\rm c}(T/T_{\rm c})^{11.8104}. \tag{31}$$

For aluminium,

$$T_{\rm c} = 416.2\,({\rm eV}), \quad \tau_{\rm c} = 3.35\times10^{-10}\,({\rm s}), \quad t_1 = \tau_{\rm c}(T/T_{\rm c})^{4.222}, \quad t_2 = \tau_{\rm c}(T/T_{\rm c})^{-0.3},$$
$$t_3 = \tau_{\rm c}(T/T_{\rm c})^{-1.4}, \quad t_4 = \tau_{\rm c}(T/T_{\rm c})^{9.1112}. \tag{32}$$

For gold,

$$T_{\rm c} = 476.3\,({\rm eV}), \quad \tau_{\rm c} = 3.1\times10^{-11}\,({\rm s}), \quad t_1 = \tau_{\rm c}(T/T_{\rm c})^{1.333}, \quad t_2 = \tau_{\rm c}(T/T_{\rm c})^{-1.0},$$
$$t_3 = \tau_{\rm c}(T/T_{\rm c})^{-1.233}, \quad t_4 = \tau_{\rm c}(T/T_{\rm c})^{4.444}. \tag{33}$$

Where the solid densities for plastic, aluminium and gold are assumed to be 1.0, 2.7 and 19.3 g/cm^3 respectively.

In ICF experiments, the radiation temperature is usually less than 200 eV. According to Eqs.(31)–(33), we know that the temperature T is lower than the critical temperature $T_{\rm c}$. Therefore, at solids density, it corresponds to the case that $T < T_{\rm c}$, and the heating process develops along the direction of solid arrow in Fig.1. The transition times t_1 and t_3 are calculated with temperature range from 56.2 to 177.8 eV, corresponding to the radiation flux range from 10^{19} to 10^{21}erg/s/cm^2 and shown in Table 1. Under the conditions that radiation pulse width is about 1ns and radiation temperature ranges from 56.2 to 177.8 eV, low and medium Z materials are in the phases of SHW-NLTE or AHW-NLTE, and high Z material is basically in the phase of AHW-LTE.

Generally, the temperature driving the material at the solids density is lower than the critical temperature, and the supersonic phase is very short with picosecond scale, seeing t_1 in Table 1. Otherwise, lowering the density of the x-ray heated material may decrease the critical temperature according to Eq.(19), and it is possible that the driven temperature $> T_{\rm c}$, then the heating process in order goes through the SHW-NLTE, SHW-LTE and AHE-LTE when the radiation duration is long enough. Consequently it is possible to produce SHW-LTE, and the optically thick requirements may be achieved, then the diffusion approximation is applicable.

Table 1. Times t_1 and t_3 of three kinds of materials with different radiation temperature.

Material	C_8H_8			Al			Au		
T/eV	56.2	100	177.8	56.2	100	177.8	56.2	100	177.8
t_1/ps	0.492	9.51	184	0.0717	0.815	9.26	1.794	3.868	8.332
t_3/ns	10.0	3.30	1.09	5.52	2.47	1.10	0.432	0.212	0.104

4. The relation between γ and the critical temperature

There should be a certain relation between γ and the critical temperature, because they are both related to the process of radiation transport in the material. Substituting Eqs.(19) and (3) into Eq.(1), we obtain

$$\gamma = \frac{F_{\rm R}}{F_{\rm M}} = \frac{\sigma T^4}{\rho\varepsilon c_{\rm s}} = \frac{\sigma T^4}{\rho\varepsilon^{1.5}} = \frac{\sigma T^{4-1.5m}}{\varepsilon_0^{1.5}\rho} = \left(\frac{T}{T_{\rm c}}\right)^{4-1.5m}. \tag{34}$$

If $T > T_{\rm c}$, γ is larger than one, since for most material $1 \le m \le 1.5$, and hence $4 - 1.5m > 0$.

$$T > T_{\rm c}. \tag{35}$$

Equation (35) is the sufficient condition for $\gamma > 1$. But if there is the phase of SHW-LTE in the heating process, it is still required that the duration of heat

wave, t_h is between t_2 and t_4, i.e.

$$t_2 < t_h < t_4. \tag{36}$$

Substituting Eqs.(19) and (20) into Eq.(22), we obtain

$$t_2 = l_0 \frac{\varepsilon_0^{s+1}}{\sigma} T^{m(s+1)-4} \rho_0^{(1-r)}. \tag{37}$$

Substituting Eqs.(3) and (18) into Eq.(37), we obtain a simple expression of t_2

$$t_2 = l_R \frac{\rho\varepsilon}{\sigma T^4}. \tag{38}$$

t_h is obtained from Eq.(6)

$$t_h = \frac{x_F}{u_h} = \frac{\alpha x_F^2 \kappa\sigma\varepsilon}{\sigma T^4}. \tag{39}$$

Substituting Eqs.(38) and (39) into the first inequation of Eq.(36), namely $t_2 < t_h$, and using Eq.(10), we obtain

$$\tau > \alpha^{-0.5} > 1. \tag{40}$$

It means that the plasma is optically thick. With the definition of the optical depth from Eq.(10), the above equations become

$$x_F > \alpha^{-0.5} l_R. \tag{41}$$

Substituting Eqs.(24) and (39) into the second inequation of Eq.(36), viz. $t_h < t_4$, it becomes

$$\tau < \alpha^{-0.5} (T/T_c)^{\frac{-3m(m+n)-4m+8n+32}{3m}}. \tag{42}$$

For most material, $1 < m < 1.5$, $1.5 < n < 2.5$, and then $-7.3 < -3m(m+n) - 4m + 8n < 5.3 \ll 32$, therefore, Eq.(42) turns approximately into

$$\tau < \sqrt{1/\alpha} (T/T_c)^{10/m}. \tag{43}$$

Combining Eqs.(40) and (43), we obtain

$$\alpha^{-0.5} l_R < x_F < \alpha^{-0.5} (T/T_c)^{10/m} l_R. \tag{44}$$

Using the doped foam, Massen *et al*[2] increased the optical depth, and optically thick plasma was produced to study the diffusive behaviour. They made the radiation transport experiments with high Z doped foam (35% lead, 65% styrene, i.e. C_8H_8), whose density was $0.08\,g/cm^3$. The scaling law for the internal energy is $\varepsilon(erg/g) = 4.05\times10^{11}T^{1.2}$ and the Rosseland mean opacity is $\kappa_R = 4.4\times10^6 T^{-1.57}\rho^{0.1}$. In this expression κ_R is in cm^2/g, T in eV, and ρ in g/cm^2. Then through Eqs.(19) and (20) we obtain $T_c = 91\,eV$ and $\tau_c = 400\,ps$. The radiation temperatures in the experiments were respectively 100, 120 and 150 eV, higher than the critical temperature T_c, and the corresponding transition times for t_2 were 356, 285 and 216 ps calculated from $t_2(ps) = 400(T/T_c)^{-1.23}$, and the transition times for t_4 were 778, 2812 and 13560 ps calculated from $t_4(ps) = 400(T/T_c)^{7.05}$, respectively. If the burn-through time t_h is shorter than t_2, the heating process only included the SHW-NLTE phase and did not include the SHW-LTE phase. If the burn-through time t_h is between t_2 and t_4, the heating process included both of the phases of the SHW-LTE. The Mach number M approximately equals to 2 by measuring the delay of radiation transport in mixture foam. The maximum of the optical depth τ is 3. From Eq.(11), we obtained $\gamma = 2.1$, larger than one, and therefore the radiative energy flux dominated the energy flux balance.

Substituting Eq.(19) into Eq.(35), we obtain

$$\rho < \sigma T^{4-1.5m}/\varepsilon_0^{1.5} = \rho_c, \tag{45}$$

where ρ_c is defined as the critical density at the temperature T. Equation (45) indicates that in order to generate the SHW-LTE phase, the density should be lower than critical density ρ_c, when the radiation temperature was determined. Equation (40) means that the heating process is optically thick, when the length of the foam should be longer than the Rosseland mean free path l_R. Therefore, Eqs.(45) and (44) may determine the density and length of the foam so that the heating process is in the phase of SWH-LTE and the diffusion approximation may be applicable.

5. Summary

In this article, we have investigated the propagation of the thermal radiation in low density material by means of simple analytic methods. The quantitative expression Eq.(11) of γ, the ratio of the radiative energy flux to the material energy flux with the Mach number and optical depth, have been found when the propagation of the heat wave is diffusively supersonic. The relation Eq.(34) between γ and the critical temperature T_c has been readily found from their expressions. The conditions of Eqs.(44) and (45), on which the heat wave in the foam is diffusively supersonic, are derived.

The results of this paper may be used to estimate the balance of radiative energy flux and the material energy flux through measuring Mach number and optical depth, and to determine the material density and

length in order to achieve the conditions of the optical thick plasma and the supersonic propagation of heat wave when the driven temperature and duration are given. The study of this paper will be helpful to the design of the experiment of the radiation transport and valuable to increase an insight into the state of matter at high temperature.

It is noted that the results in Section 2 hold true only for the diffusive supersonic heat wave. The four regimes are reviewed in Section 3 and can be applied to any process heated by thermal radiation no matter how supersonic or ablative, diffusive or non-diffusive. Equation (34) in Section 4 is applied to all four regimes.

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