



HAL
open science

Calculating the temperature of strongly radiative shocks

Paul Mabey, Thibault Michel, Bruno Albertazzi, Émeric Falize, Nicolas Charpentier, Michel Koenig

► **To cite this version:**

Paul Mabey, Thibault Michel, Bruno Albertazzi, Émeric Falize, Nicolas Charpentier, et al.. Calculating the temperature of strongly radiative shocks. *Physics of Plasmas*, 2020, 10.1063/5.0008301 . hal-03026121

HAL Id: hal-03026121

<https://hal.science/hal-03026121>

Submitted on 26 Nov 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Calculating the temperature of strongly radiative shocks

Paul Mabey,^{1, a)} Thibault Michel,¹ Bruno Albertazzi,¹ Emeric Falize,² Nicolas Charpentier,² and Michel Koenig^{1, 3}

¹⁾LULI - CNRS, Sorbonne Universités, Ecole Polytechnique, Institut Polytechnique de Paris - F-91128 Palaiseau Cedex, France

²⁾CEA, DAM, DIF, F-91297 Arpajon, France

³⁾Graduate School of Engineering, Osaka University, Osaka, 565-0871, Japan

(Dated: 23 June 2020)

A new method of calculating the temperature of strongly radiative shocks (Mihalas number of order unity or lower) is proposed. By including ionization, radiative energy and radiative flux terms in the Rankine-Hugoniot jump conditions across the shock front, a new, self-consistent method of calculating the temperature of radiative shocks is developed. The method is compared to those used to calculate temperature in previous works using similar methods, including those which partially included radiative and/or ionization effects. The method is also compared to experimental data, taken from the literature, as well as SESAME equation of state tables and radiative hydrodynamics simulations. The results show the importance of including all radiative terms for the case of strongly radiative shocks. This result has important implications for the design and interpretation of future laboratory experiments where ever faster radiative shocks may be generated. Previously unseen phenomena could be accessible when the radiative energy plays a significant role in the system.

I. INTRODUCTION

Radiative shocks are present in a myriad of astrophysical systems such as supernova explosions^{1,2} and remnants³⁻⁵, young stellar objects⁶, cataclysmic variables^{7,8}, and black holes⁹. These phenomena all represent mechanisms to inject large amounts of energy back into the interstellar medium (ISM). They therefore have a significant impact on a multitude of processes, including star formation, which is thought to be triggered by the interaction between shock waves and molecular clouds¹⁰. Direct astronomical observation of these systems is challenging for numerous reasons. The frequency of detectable events as well as their distance from us, and hence the resolution with which we can observe them, are limiting factors. Moreover, the downstream region often becomes optically thick to its own radiation, preventing it from escaping the system, thus posing further problems. For these reasons, simulations, theoretical studies and terrestrial experiments have all been employed to study radiative shocks. The dynamics of these shocks waves are influenced by their strong radiative energy flux and/or pressure, and therefore purely hydrodynamic approaches are unlikely to produce reliable results. Coupled with the large range of spatial and temporal length scales associated with many of these phenomena, numerical modelling through simulations is also challenging, even with modern computers⁵. Nevertheless, increasing computational complexity has allowed progressively more detailed simulations to be carried out¹¹.

In parallel to this, theoretical studies on the effect of radiation on shock waves **have been performed since the 1950s (see e.g. the book by Zel'dovich and Raizer¹² for a thorough overview)**. Approximate expressions for the density and temperature of air compressed by strong shock waves, taking dissociation and ionization into account, were proposed¹³. Using highly idealized conditions, the structure of these shocks was

considered, and the existence of a heated region ahead of the shock front was predicted¹⁴. Since then, the field has garnered significant interest and there now exists a large body of work on the subject. With regards to the structure of radiative shocks, one now often distinguishes three separate zones, as shown by fig 1. The pre-shock and post-shock regions, stretching out to infinity ahead and behind the shock region in the idealized case, are separated by a precursor or transition zone of width δ . This region is caused by radiation escaping from the heated, post-shock region to the cooler, pre-shock region, subsequently rising its temperature over a characteristic length ahead of the shock front. For strongly radiative shocks with very high Mach numbers,¹⁵ showed that these three regions could begin to merge together forming continuous temperature and density profiles. Thermodynamic quantities have been shown to depend intimately on the amount of radiation re-absorbed by the system after emission, and therefore on the optical depth. For example,¹⁶ predicted an upper-bound in the shock-induced compression ratio for optically thick systems such as stellar interiors or supernovae (where the length of the system is larger than the mean free path for the thermal radiation and so is trapped in the material), the shock induced compression ratio, while no such bound exists in optically thin systems. Work has subsequently been done to summarize the different ways to classify different regimes of radiative shocks^{17,18,19} considered the energy balance of the three region system although neglected to consider the role of radiation energy therein. Despite the stationary nature of the vast majority of these studies, since energy may be lost from the system, radiative shocks are inherently unstable over a sufficiently long timescale, and hence are prone to instabilities²⁰. Astrophysical studies of radiative shocks (i.e. line-emission-dominated and optically thin) in specific environments such as stellar atmospheres^{21,22} or including the effect of electron thermal conduction²³ have also been carried out.

Studies of radiative shocks in the laboratory have also progressed with improvements in laser technology, thus also increasing our knowledge of the subject. Different target designs have been employed including clusters²⁴, gas cells²⁵,

^{a)}Electronic mail: paul.mabey@polytechnique.edu

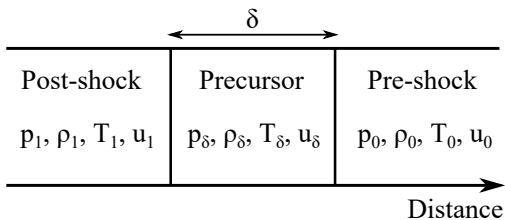


FIG. 1. Simple schematic structure of a radiative shock wave with three regions, each having their own pressure, p ; density, ρ ; temperature, T and flow velocity, u .

and shock tubes²⁶. These experiments have served to confirm many previous theoretical predictions. Radiative effects such as the existence of shock precursor regions^{27,28} as well as velocity domain oscillations²⁹ have been observed. Recent experiments, with larger radiation energies, have shown other effects, less thoroughly discussed in the literature, such as the deceleration due to radiative losses³⁰. However, there is still uncertainty surrounding the temperature of radiative shocks in such experiments due to the paucity of directly experimentally measured data (see for example the most recent experiments in the field^{30,31} which do not make any attempt to measure this parameter). This represents a significant problem, as the temperature of a radiative shock is of prime importance in determining the extent to which the shock is in fact radiative. This is crucial to both the design of future experimental campaigns as well as the understanding of experimental data that is already available. Whilst technically challenging, temperature measurements of high energy plasmas have been shown to be perfectly achievable^{32,33} and we hope to see more of them in future work. Currently, other experimental parameters such as the shock speed or post-shock density are more straightforward to determine and are frequently obtained. Therefore, theoretical approaches, often applying the Rankine-Hugoniot jump conditions, are typically invoked to determine the temperature of radiative shocks in an experimental context (see e.g.²⁶). There exists, however, a variety of said approaches, many of which neglect crucial radiative effects.

In this paper, we propose a new method of calculating the temperature of radiative shocks, in the context of laboratory experiments, by properly including the effects of radiation in the Rankine-Hugoniot (RH) jump conditions across a shock front in a self-consistent manner. This represents the first such approach to include the radiation energy in the conservation equations. With future experiments at high-power laser facilities able to generate ever stronger radiative shocks, the inclusion of this term is shown to be of particular importance.

II. APPLICATION OF THEORY

Employing the RH jump conditions in the purely hydrodynamic case (that is in the absence of any radiative or ionization terms), the post-shock temperature, T_1 as a function of the

shock speed, u_s may be written as

$$k_B T_1 = \frac{2(\gamma-1)}{(\gamma+1)^2} \frac{A m_p}{(1+Z_1^*)} u_s^2, \quad (1)$$

where Z_1^* is the mean ionization state of the post-shock gas with atomic number Z and atomic weight A , γ the adiabatic index, m_p the proton mass, k_B the Boltzmann constant, σ the Stefan-Boltzmann constant,

Eq. 1. provides a route to calculate the degree to which a shock of a particular speed might experience significant radiative effects^{16,34}. Given complete control over experimental conditions and thus knowledge about the pre-shock conditions, measuring the experimental shock speed is therefore sufficient to determine the post-shock temperature. The problem here is the following: the derivation used to reach this formula neglects radiation and ionization in the energy balance equation relating the pre-shock and post-shock regions. Therefore if the shock speed is high enough for radiative terms to be important, this method is inappropriate. This method therefore cannot be used to determine the temperature of shocks, one might suspect to be radiative in nature. Indeed, laboratory experiments have already showed that radiation has a significant impact on shock speed and that a modified version of the Rankine-Hugoniot jump conditions are necessary³⁰, and this comes as no surprise.

In order to quantify radiative effects of a laboratory system, two dimensionless numbers are introduced^{16,18,35,36}. The first, the Mihalas number R , is the ratio between the thermal energy density and the radiative energy density. In the case of a black-body, it is defined as

$$R = \frac{1}{\gamma-1} \frac{(1+Z^*)k_B}{A m_p} \frac{\rho c}{4\sigma T^3 g(\tau)}, \quad (2)$$

ρ is the mass density, c the speed of light, σ the Stefan-Boltzmann constant, and $g(\tau)$ a measure of the degree to which the real radiative energy differs from the black body approximation as a function of the optical depth (τ). The second, the Boltzmann number Bo , is the ratio between the enthalpy flux and the radiative flux and is defined as

$$Bo = \frac{\gamma}{\gamma-1} \frac{(1+Z^*)k_B}{A m_p} \frac{\rho u_s}{\sigma T^3 f(\tau)}, \quad (3)$$

where $f(\tau)$ is the emissivity. The two quantities have similar forms and indeed are related by $R = cBo f(\tau)/4u_s g(\tau)$. In order to maximize radiative effects, one therefore requires a high temperature, low density, high- A gas.

The functions $f(\tau)$ and $g(\tau)$ allow the above formulae to be applicable to grey-body emitters by taking into account deviations from the black-body approximation³⁷. They therefore allow the inclusion of a wealth of microphysics in a very straightforward manner. Their forms are given by

$$f(\tau) = 1 + e^{-\tau}(\tau-1) - \tau^2 E_1(\tau), \quad (4)$$

and

$$g(\tau) = 1 - e^{-\tau} + \tau E_1(\tau), \quad (5)$$

where

$$E_1(\tau) = \int_{\tau}^{\infty} \frac{e^{-\tau}}{\tau} . \quad (6)$$

It is not necessary to be particularly optically thick in order to consider $g(\tau) \approx f(\tau) \approx 1$ (for example $f(1) = 0.78$, $f(2) = 0.94$, $f(3) = 0.982$, $f(4) = 0.994$). This is the case in general in laboratory experiments¹⁸ and so we shall henceforth apply this approximation.

In order to proceed, we add the appropriate radiation and ionization terms to the equations for mass, momentum and energy conservation across the shock front:

- The pressure of the system now not only includes the thermal pressure, p_{th} , but also the radiation pressure, p_{rad} .
- The total internal energy of the system is expanded to include the ionization energy, E_{ion} .
- The radiative flux, F_{rad} , is also taken into account in the energy equation.

- Finally, the radiative energy, E_{rad} is also added to the energy equation.

The inclusion of terms similar to these is not novel. For example¹⁹ considered the so called *flux-dominated regime* in which the radiative energy fluxes exceed the material energy fluxes but the radiation pressure remains negligible, while³⁸ included a thorough treatment of ionization effects in high- Z gases, in the absence of radiative fluxes. Recalling the definition of the dimensionless numbers Bo and R we note that ignoring the radiative flux term is valid when $Bo \gg 1$, while ignoring the radiative energy term is valid when $R \gg 1$. Given the relationship between the two, $R \gg Bo$ for non-relativistic shock speeds. Similar to the flux-dominated regime, we define the *strongly radiative* regime as the one in which not only is the radiative flux important but also the radiation energy density becomes comparable to the material energy density, i.e. $R \sim 1$ or lower, and thus the inclusion of all of the terms outlined above is necessary.

The modified RH jump conditions for the conservation of mass, momentum and energy may therefore be written out as the following:

$$\rho_1 u_1 = \rho_0 u_0 \quad (7)$$

$$\rho_1 u_1^2 + p_{th,1} + p_{rad,1} = \rho_0 u_0^2 + p_{th,0} + p_{rad,0} \quad (8)$$

$$(\rho_1 (\varepsilon_1 + u_1^2/2 + E_{ion,1}) + p_{th,1} + p_{rad,1} + E_{rad,1}) u_1 + F_{rad,1} = (\rho_0 (\varepsilon_0 + u_0^2/2 + E_{ion,0}) + p_{th,0} + p_{rad,0} + E_{rad,0}) u_0 + F_{rad,0} \quad (9)$$

where ε is the specific energy and the subscripts 0 and 1 denote the pre-shock and post-shock regions respectively.

We recall that the thermal pressure may be written as

$$p_{th} = (\gamma - 1) \rho \varepsilon = \frac{\rho k_B T (1 + Z^*)}{A m_p} , \quad (10)$$

while the radiative terms also take their usual forms

$$E_{rad} = 3 p_{rad} = g(\tau) 4 \sigma T^4 / c , \quad (11)$$

$$F_{rad} = f(\tau) \sigma T^4 . \quad (12)$$

These formulae implicitly assume that the radiative is emitted and reabsorbed isotropically. At sub-relativistic speeds and in the absence of any detailed quantum effects, isotropic emission needs no motivation however uniform absorption implies that the optical depth is constant everywhere. As stated, previously we assume that both the pre-shock and post-shock media are optically thick and hence this also implies that the absorption of radiation ought to be uniform. Moreover, we also assume that the two media can themselves be described using constant thermodynamic values (i.e with no spatial variation). In the context of fig. 1, we are therefore interested in their values at distances, D , away from the transition region, such that $D/\delta \gg 1$.

We now require an expression for the mean ionization state as well as the ionization energy. In astrophysics, where hydrogen and helium dominate, one can assume that the gas is fully ionized ($Z^* = Z$), and thus the equation of state is well known. However, this is not the case in general. In many laboratory experiments, high- Z gases such as xenon are used in order to study radiative effects. In this case, $Z^* < Z$, and so assuming a fully ionized gas is not a suitable approximation.

Instead, we follow the prescription proposed by More, which itself is based on an extended Thomas-Fermi model^{9,37}. Although this method was originally based on higher density materials, it has nevertheless been shown to give accurate results in this regime³⁹. We have

$$Z = \phi(x) Z^* , \quad (13)$$

where $\phi(x)$ is a fitting function that depends on T, Z, ρ and A , as defined in⁴⁰. Explicitly, it may written as

$$\phi(x) = x / (1 + x + \sqrt{1 + 2x}) , \quad (14)$$

where x is written out using the form, αQ^β , where α, β and Q are fitting constants whose values are determined by fitting with experimental data⁴⁰.

The ionization energy may also be written as

$$E_{ion} = Z^{4/3} I_0 Z^* / Z , \quad (15)$$

where

$$I_0 = \frac{2}{3} E_H \frac{x^2}{(1-x)^{2/3}}, \quad (16)$$

and $E_H = 13.6$ eV.

Next, we assume a density compression ratio of 7, as calculated theoretically in³⁷. A similar value was found by³⁸ for strong shocks when taking into account detailed ionization effects, although small deviations to this value were found for slower speeds. We also assume that the polytropic index of the gas, γ , takes the same value on both sides of the shock, such that eq. 10 holds in both cases (i.e. $\gamma_0 = \gamma_1 = \gamma = 5/3$).

Finally, we require complete knowledge of the pre-shock medium (ρ, T, u_0), we have all that is required to solve eqs. 7-9 in order to obtain the post-shock temperature as a function of the shock speed. Given we approximate the shock front as a discontinuous jump, the former represents the initial conditions of any experiment, which are typically well controlled (i.e. the gas is at rest at room temperature at a precisely measured pressure). By plugging eqs. 7 and 8 into eq. 9 and solving for T_2 , in principle this is possible to do analytically analogous to the purely hydrodynamic case (eq.1). However, the resulting equation is hopelessly complicated and opaque to any analysis. Here, we perform numerical calculations using Matlab in order to generate our results, [with a link to the code provided in sec. V](#). We note that, although the equation is quartic in nature, there exists only one physically meaningful root ($T_2 \in \mathbb{R}^+$).

We note several assumptions implicitly made by the use of the RH jump conditions. Firstly, any shock heats particles in proportion to their mass, so the ion heating by the shock is much larger than the direct heating of the electrons. As a result, there is also a spatial scale downstream of the density jump, on which the electron and ion temperatures equilibrate. However, this scale can be much smaller than the radiative scales²⁸, (see e.g.³⁷ and so we ignore electron-ion equilibration here. Electron heat conduction can also introduce a spatial scale, significant when a radiating shock is driven outward from a hot, low-density source⁴¹. For piston-like radiative shock generators, such as gas guns or nanosecond lasers, this effect is negligible however. Finally, we note that our approach does not take into account the stability (or lack thereof) of radiative shocks. The conditions considered here can be thought of as those encountered upon the formation of the radiative shock, on timescales shorter than those associated with the growth of any instabilities. Previous experiments in the field show that said shocks may safely be considered stable on the timescale of several nanoseconds^{26,30}.

III. RESULTS

In order to demonstrate the importance of properly including radiative effects in relevant studies, we plot the post-shock temperature as a function of the shock speed for various models and experimental studies:

- The purely hydrodynamic case, as given by equation 1. This calculation has commonly been employed in-

terpreting laboratory experiments, starting with²⁷ and more recently by³⁴.

- A more contemporary flux-balancing model, based on work by⁴² and first employed to analyse experiments of this type by²⁶. This approach notes that a constant radiative precursor width implies that the radiative flux from the shock, and therefore the post-shock temperature, is approximately constant over the observed time. The latter can therefore be estimated by equating the radiative loss flux (roughly twice the black body emission) to the kinetic energy flux of incoming particles (half the product of the pre-shock mass density and the shock velocity). This gives

$$T_1 = \left(\frac{\rho_0 u_s^3}{4\sigma} \right)^{1/4} \quad (17)$$

This method takes into account F_{rad} and so is well-suited to the regime where Bo is small. However, it also assumes that $p_{rad} = E_{rad} = 0$ and hence ought to break down as $R \rightarrow 1$ when these terms can no longer be ignored.

- Calculations including the detailed effects of ionization and excitation, as well as the radiation energy and pressure³⁸. The ionization structure and excitation energies are calculated from the local temperature and density, using the Screened Hydrogenic Model. Note that the contribution of the radiative fluxes were neglected in this approach.
- Data taken from the SESAME equation of state tables. This database meshes together a variety of theoretical models, simulations and experiments using interpolation techniques. The tables provide a mathematical relationship between two or more of that matter's state functions, such as its temperature, pressure, volume, or internal energy, over a broad range of materials and expansive regions of pressure and temperature. Full details may found on the Los Alamos website, where the library is presently being offered to all interested users free of charge⁴³.
- Shock temperatures measured by the 2D radiative hydrodynamics code, FCI2⁴⁴. Simulations included radiation via a multi-group algorithm (300 groups), with relevant opacities and equations of state taken from in-built tables. In the simulations, a supported, planar radiative shock in xenon gas was generated by the breakout of a shock travelling through a solid target into a gas-filled cell. The system was driven using the laser energy deposition modules available in the code, thus modelling a realistic laboratory experiment.
- Using the method as outlined in sec. II, but only including the ionization terms and not the radiative ones (F_{rad} , P_{rad} and E_{rad} are set to zero artificially).
- Including the full suite of physics, including all ionization and radiative terms as defined in sec. II (labelled as *with radiation* in fig. 2).

- Two experimental studies which measured the temperature of radiative shocks in high-Z gases. In the first, absolutely calibrated self-emission from the post-shock region was used to measure the temperature in shocked xenon³². In the second experiment, an X-ray Thomson scattering diagnostic was used to probe shocked argon gas. The temperature was determined by comparing the measured spectrum with simulations of varying temperature and employing a best-fit routine³³.

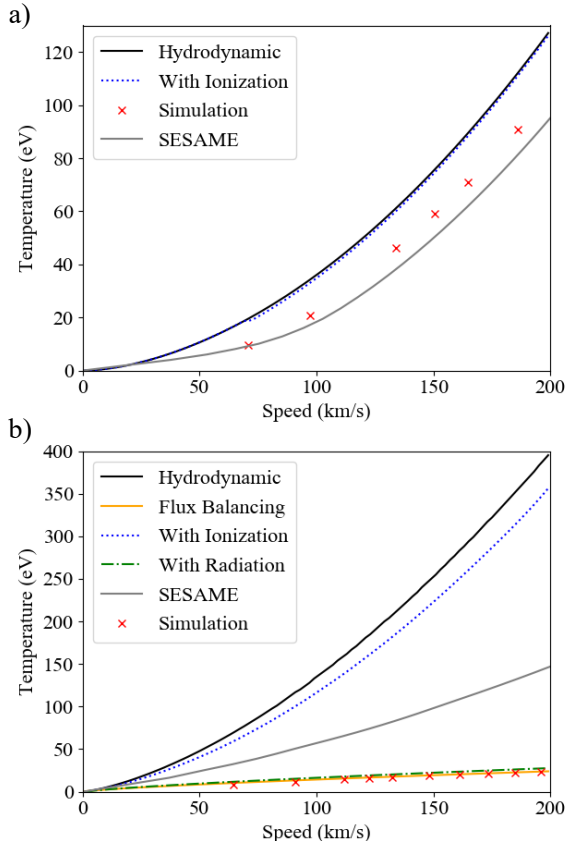


FIG. 2. Post-shock temperature of radiative shocks in two ambient media obtained by various different methods. a) 1 bar of helium gas and b) 30 mbar of xenon gas were chosen to have the same mass density. The former represents the control case, while the latter is chosen to maximise radiative effects. In both cases the pre-shocked gas is at rest at room temperature (300 K)

We first consider the two cases of a shock propagating through 30 mbar xenon and 1 bar helium gas. The pressures are chosen such that the mass density between the two cases is the same. As discussed in sec II, high A gases should be expected to undergo larger radiative effects. Thus the helium gas is the control, non-radiative case, while xenon is selected to maximize radiative effects. This reasoning is commonplace in experiments designed to study such effects.

The results are plotted in fig. 2. In the case of xenon (panel b)), since some fraction of the shock energy is used up in order to ionize the medium or emit radiation, the addition of the ionization and radiation terms act to lower the temperature of

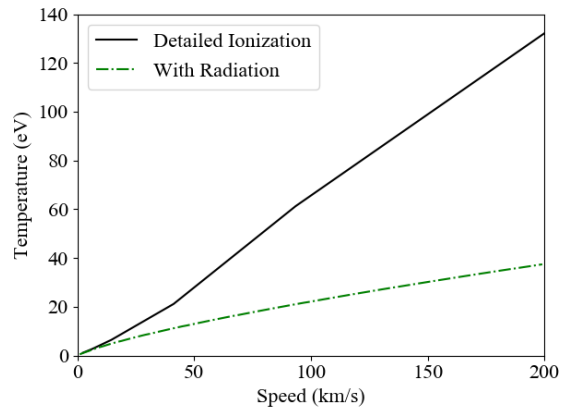


FIG. 3. Post-shock temperature of radiative shocks in 320 mbar of xenon gas with the method outlined, with radiation and ionization terms, as well as with ionization terms only, compared with calculations performed by³⁸. The pre-shocked gas is at rest at a pre-heated temperature of 0.1 eV (or 1160 K)

the shock for a given speed. For speeds lower than 20 km/s, this effect is small and hence the purely hydrodynamic calculation seems a good approximation. Inversely, for speeds above 100 km/s this difference is significant, with radiative effects becoming more important. Moreover, our approach agrees well with the simulated values using FCI2, giving us confidence in its fidelity. We note that the SESAME tabulated data are best adapted to a higher density regime than the one studied here, and hence they must be treated with caution. As for the helium gas, we note that the introduction of the ionization terms have no effect on the post-shock temperature compared to the purely hydrodynamic solution. The latter predicts a slightly higher temperature than the SESAME data as well as the fluid code although the differences are small and the qualitative shape of the curve is the same.

We also note a vast difference between the two methods found in the literature. The more recent flux balancing approach predicts a significantly lower temperature than the previously-used hydrodynamic model ($T \propto u_s^2$ vs $T \propto u_s^{3/4}$). For the parameters considered here, the former predicts a temperature of 23.5 eV at a speed of 200 km/s. This compares to a value of 27.7 eV, as calculated by our method including radiative and ionizing effects and so corresponds to a difference of 16 %. Thus the flux balancing calculation is evidently an improvement over previous methods, and give a good estimate of the true value.

The calculations performed by³⁸ assume a pre-shock gas at a temperature of 0.1 eV and therefore the results do not directly correspond to the case of typical experimental conditions (although the authors also state that this is unlikely to make a difference). Nevertheless, we are able to compare their results to ours, as shown in fig. 3. The graph demonstrates that despite the model's inclusion of more detailed ionization physics, the reduction in temperature is still less than in our model. This is very likely due to the lack of radiation flux terms in the former, thus also pointing to the importance of

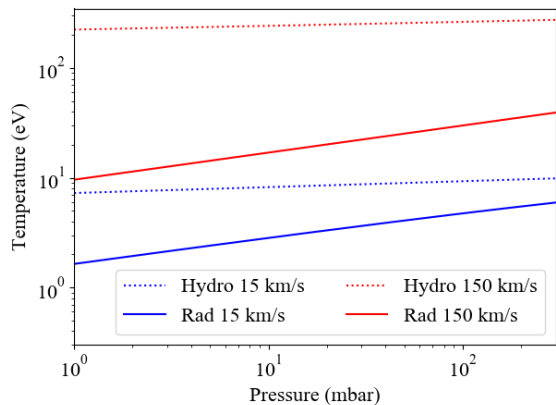


FIG. 4. Post-shock temperature of radiative shocks in xenon gas as a function of density for two different velocities, as calculated within the purely hydrodynamic approximation as well as with the inclusion of radiative and ionization terms.

their inclusion in order to correctly determine the post-shock temperature. Indeed, our results suggest that radiation is more important than ionization for the parameter regimes considered here.

It is also instructive to consider the effect of increasing pressure on the post-shock temperature (see fig. 4) in more detail. The gradual increase in temperature in the purely hydrodynamic approximation, as given by eq. 1, stems from the change in ionization state with pressure. With the radiative terms added, the dependence is more marked, although the two approaches appear to converge at higher pressures. This is because at these pressures, there the material flux is higher and thus the ratio of the radiative flux to the material flux is lower, reducing the relative importance of the latter.

We also compare our results with the two laboratory experiments studying radiative shocks in high-Z gases as described previously. The results of our calculations are displayed in table I. Our method shows good agreement with the experimentally measured values while the purely hydrodynamic model, especially at higher velocities, breaks down. These two experiments are quite different in nature (gas fill, temperature diagnostic etc.) and hence this agreement is quite satisfying.

TABLE I. Experimentally measured shock velocities and temperatures at different gas pressures, as taken from Refs.^{32,33}. Shock temperatures calculated without radiative effects using eq. 1 (hydro), as well as with radiative effects using the method outlined in Sec. II, are also shown.

Ref	Gas	u_s (km/s)	p_0 (bar)	T (eV)		
				Exp	Hydro	Rad
³²	Xe	45	0.20	$9 \pm 15\%$	46	14
³²	Xe	41	0.20	$11 \pm 15\%$	40	13
³²	Xe	60	0.10	$15 \pm 15\%$	68	15
³²	Xe	78	0.10	$19 \pm 15\%$	101	18
³³	Ar	163	0.5	$34 \pm 14\%$	212	35

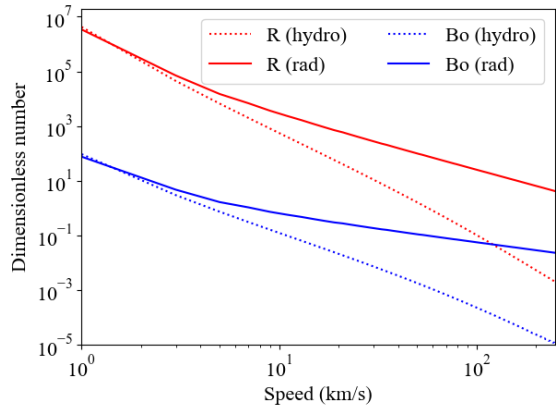


FIG. 5. Boltzmann and Mihalas numbers calculated using the hydrodynamic temperature, B_{hyd}, R_{hyd} , as well as the temperature calculated when including radiative and ionization effects, B_{rad}, R_{rad} for the case of 30 mbar xenon gas.

Although further comparison with experimental data would be desirable, there is a paucity of studies in the literature in which the temperature of a radiative shock is directly measured experimentally. Although measuring temperature is technically feasible in plasma physics experiments, the majority of methods require the absolute calibration of a complete optical system in a very short time frame. For this reason, this undertaking is rarely carried out, with experimenters instead opting to extract temperature by comparison with simulations.

We are now in a position to redetermine the two dimensionless numbers, Bo and R , introduced previously, as a function of shock speed in xenon. We perform this for the two extreme cases of the purely hydrodynamic model (used for example in⁴⁶) together with our approach including all additional physics, with the results displayed in fig 5. The addition of these terms lowers the temperature and therefore increases the value of these two parameters, as expected. The critical speed, for which Bo or $R = 1$, is therefore higher than if one calculates the speed in the purely hydrodynamic case. Qualitatively this is already known, however the extent of these deviations (four or more orders of magnitude) at shock speeds above 100 km/s are noteworthy.

Table II displays these two parameters calculated for the

TABLE II. Boltzmann (Bo) and Mihalas (R) numbers calculated from parameters taken from experimental studies in the literature from 2004 to 2019

Ref	Gas	p_0 (bar)	u_s (km/s)	T (eV)	Bo	R
²⁸	Xe	0.10	65	16	0.12	85
²⁸	Xe	0.20	65	19	0.15	105
³²	Xe	0.10	78	18	0.10	59
⁴⁵	Xe	1.0	140	50	0.11	36
³³	Ar	0.50	163	35	0.10	29
³¹	Xe	0.30	80	24	0.13	78
³⁰	Xe	0.03	165	24	0.03	9

various radiative shock experiments found in the literature over the past 15 years. All of these studies were aimed at studying a regime in which one observes a radiative precursor ahead of the shock front. Indeed, it has been shown beyond any reasonable doubt that the systems shown in these experiments are subject to considerable radiative effects. This regime is characterized by a high radiative flux and hence a low value of Bo . However, table II shows that in almost all experiments carried out up to the present, $R \gg 1$. That is to say the radiative energy density was almost negligible compared to the thermal energy density. It is therefore reasonable to expect additional radiative effects to occur for strongly radiative shocks where $R \sim 1$, as this is a regime for which there is no experimental data.³⁰ describes an experiment in which $R = 9$; i.e. radiative energy losses represented approximately 10% of the total energy of the system, compared with $\sim 1\%$ in previous works. In this experiment, the radiative energy density was sufficient to decelerate a strong planar shock. Such a phenomenon had not been seen beforehand, likely due to the high Mihalas numbers in previous experiments. This experiment therefore provides evidence to support the claim that progressing towards the regime in which $R \sim 1$ could unveil new, hitherto unseen, physical processes. Appropriately designed experiments at large-scale laser facilities such as the NIF or LMJ, capable of launching shocks upwards of 200 km/s could reach these conditions. Experimental temperature measurements at these conditions will be necessary in order to validate simulations and models such as ours.

IV. CONCLUSIONS

Radiative shocks, ubiquitous in astrophysical systems, have previously been studied extensively both experimentally and theoretically. Calculating the expected post-shock temperature of said shocks is crucial in designing experiments and interpreting data and many methods have been developed with this goal in mind. Thus far, however, technical constraints have limited experimental studies to the regime in which the radiation energy is unimportant ($R \gg 1$). Therefore, corresponding theoretical approaches have tended to neglect terms relating to the radiative energy. In this work, we have therefore proposed an approach designed to include this effect, as part of a complete description radiative and ionization phenomena in idealized optically thick systems. While our model still has limitations, it shows good agreement with hydrodynamic simulations and, where possible, experimental data.

By calculating the Mihalas and Boltzmann numbers using our method, a clear road-map for future studies emerges. Although many past experiments have been able to probe the $Bo < 1$ regime, none have been able to reach $R \sim 1$. In order to advance our understanding of astrophysical systems, where radiative energy densities are very high, experiments must probe further into the $R \sim 1$ or even $R < 1$ regime. Previous methods of calculating the post-shock temperature and therefore this parameter would not be appropriate for this new, strongly radiative regime.

The data that support the findings of this study are available

from the corresponding author upon reasonable request.

V. SUPPLEMENTARY INFORMATION

See supplementary material for the matlab files used to calculate the temperature using the RH jump conditions including radiative and/or ionization terms as well as in the purely hydrodynamic case.

- ¹H. A. Bethe, “Supernova shock. viii.” *The Astrophysical Journal* **490**, 765 (1997).
- ²K. Schawinski, S. Justham, C. Wolf, P. Podsiadlowski, M. Sullivan, K. C. Steenbrugge, T. Bell, H.-J. Röser, E. S. Walker, P. Astier, *et al.*, “Supernova shock breakout from a red supergiant,” *Science* **321**, 223–226 (2008).
- ³R. A. Chevalier, “The interaction of supernovae with the interstellar medium,” *Annual Review of Astronomy and Astrophysics* **15**, 175–196 (1977).
- ⁴J. M. Blondin, E. B. Wright, K. J. Borkowski, and S. P. Reynolds, “Transition to the radiative phase in supernova remnants,” *The Astrophysical Journal* **500**, 342 (1998).
- ⁵D. F. Cioffi, C. F. McKee, and E. Bertschinger, “Dynamics of radiative supernova remnants,” *The Astrophysical Journal* **334**, 252–265 (1988).
- ⁶S. Orlando, R. Bonito, C. Argiroffi, F. Reale, G. Peres, M. Miceli, T. Matsakos, C. Stehle, L. Ibgui, L. de Sa, J. P. Chieze, and T. Lanz, *Astron. Astrophys.* **559**, A127 (2013).
- ⁷C. Busschaert, E. Falize, C. Michaut, J. M. Bonnet-Bidaud, and M. Mouchet, *Astron. Astrophys.* **579**, A25 (2015).
- ⁸L. Van Box Som, E. Falize, J. M. Bonnet-Bidaud, M. Mouchet, C. Busschaert, and A. Ciardi, “Numerical simulations of high-energy flows in accreting magnetic white dwarfs,” *MNRAS* **473**, 3158–3168 (2018), arXiv:1709.09554 [astro-ph.SR].
- ⁹T. Okuda, V. Teresi, E. Toscano, and D. Molteni, “Radiative shocks in rotating accretion flows around black holes,” *Publications of the Astronomical Society of Japan* **56**, 547–552 (2004).
- ¹⁰T. Nagakura, T. Hosokawa, and K. Omukai, “Star formation triggered by supernova explosions in young galaxies,” *Monthly Notices of the Royal Astronomical Society* **399**, 2183–2194 (2009).
- ¹¹S. Orlando, M. Miceli, M. Pumo, and F. Bocchino, “Supernova 1987a: a template to link supernovae to their remnants,” *The Astrophysical Journal* **810**, 168 (2015).
- ¹²I. Zel’dovich and Y. Raizer, *Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena*, Dover Books on Physics (Dover Publications, 2002).
- ¹³I. B. Zel’dovich, “Shock waves of large amplitude in air,” *Soviet Phys. JETP* **5** (1957).
- ¹⁴I. P. Raizer, “On the structure of the front of strong shock waves in gases,” *Soviet Phys. JETP* **5** (1957).
- ¹⁵S. Bouquet, R. Teyssier, and J. P. Chieze, “Analytical study and structure of a stationary radiative shock,” *The Astrophysical Journal Supplement Series* **127**, 245 (2000).
- ¹⁶R. P. Drake, “Radiative shocks in astrophysics and the laboratory,” in *High Energy Density Laboratory Astrophysics* (Springer, 2005) pp. 49–59.
- ¹⁷R. Drake, F. Doss, R. McClarren, M. Adams, N. Amato, D. Bingham, C. Chou, C. DiStefano, K. Fidkowski, B. Fryxell, T. Gombosi, M. Grosskopf, J. Holloway, B. van der Holst, C. Huntington, S. Karni, C. Krauland, C. Kuranz, E. Larsen, B. van Leer, B. Mallick, D. Marion, W. Martin, J. Morel, E. Myra, V. Nair, K. Powell, L. Rauchwerger, P. Roe, E. Rutter, I. Sokolov, Q. Stout, B. Torralva, G. Toth, K. Thornton, and A. Visco, “Radiative effects in radiative shocks in shock tubes,” *High Energy Density Physics* **7**, 130–140 (2011).
- ¹⁸C. Michaut, E. Falize, C. Cavet, S. Bouquet, M. Koenig, T. Vinci, A. Reighard, and R. P. Drake, *Astrophys. Space Sci.* **322**, 77 (2009).
- ¹⁹R. P. Drake, “Energy balance and structural regimes of radiative shocks in optically thick media,” *IEEE Transactions on plasma science* **35**, 171–180 (2007).

- ²⁰E. Bertschinger, “On the structure and stability of radiative shock waves,” *The Astrophysical Journal* **304**, 154–177 (1986).
- ²¹E. Huguet and J.-P. Lafon, “Radiative shocks in atomic and molecular stellar-like atmospheres. viii. a self-consistent comprehensive model.” *Astronomy and Astrophysics* **324**, 1046–1058 (1997).
- ²²A. Fokin, G. Massacrier, and D. Gillet, “Radiative cooling of shocked gas in stellar atmospheres-ii. self-consistent lte shock wake model with fe lines and h continua contributions,” *Astronomy & Astrophysics* **420**, 1047–1059 (2004).
- ²³Y. A. Fadeyev, H. Le Coroller, and D. Gillet, “The structure of radiative shock waves-iv. effects of electron thermal conduction,” *Astronomy & Astrophysics* **392**, 735–740 (2002).
- ²⁴T. Ditmire, K. Shigemori, B. Remington, K. Estabrook, and R. Smith, “The production of strong blast waves through intense laser irradiation of atomic clusters,” *The Astrophysical Journal Supplement Series* **127**, 299 (2000).
- ²⁵M. Koenig, T. Vinci, A. Benuzzi-Mounaix, S. Lepape, N. Ozaki, S. Bouquet, L. Boireau, S. Leygnac, C. Michaut, C. Stehle, *et al.*, “Radiative shock experiments at luli,” in *High Energy Density Laboratory Astrophysics* (Springer, 2005) pp. 69–74.
- ²⁶R. Drake, F. Doss, R. McClarren, M. Adams, N. Amato, D. Bingham, C. Chou, C. DiStefano, K. Fidkowski, B. Fryxell, *et al.*, “Radiative effects in radiative shocks in shock tubes,” *High Energy Density Physics* **7**, 130–140 (2011).
- ²⁷P. Keiter, R. Drake, T. Perry, H. Robey, B. Remington, C. Iglesias, R. Wallace, and J. Knauer, “Observation of a hydrodynamically driven, radiative-precursor shock,” *Physical review letters* **89**, 165003 (2002).
- ²⁸S. Bouquet, C. Stéhlé, M. Koenig, J.-P. Chièze, A. Benuzzi-Mounaix, D. Batani, S. Leygnac, X. Fleury, H. Merdji, C. Michaut, F. Thais, N. Grandjouan, T. Hall, E. Henry, V. Malka, , and J.-P. J. Lafon, *Phys. Rev. Lett* **92**, 225001 (2004).
- ²⁹M. Hohenberger, D. Symes, J. Lazarus, H. Doyle, R. Carley, A. Moore, E. Gumbrell, M. Notley, R. Clarke, M. Dunne, *et al.*, “Observation of a velocity domain cooling instability in a radiative shock,” *Physical review letters* **105**, 205003 (2010).
- ³⁰T. Michel, B. Albertazzi, P. Mabey, G. Rigon, F. Lefevre, L. V. B. Som, P. Barroso, S. Egashira, R. Kumar, C. Michaut, *et al.*, “Laboratory observation of radiative shock deceleration and application to sn 1987a,” *The Astrophysical Journal* **888**, 25 (2019).
- ³¹F. Suzuki-Vidal, T. Clayson, C. Stehlé, G. F. Swadling, J. M. Foster, J. Skidmore, P. Graham, G. C. Burdiak, S. V. Lebedev, U. Chaulagain, R. L. Singh, E. T. Gumbrell, S. Patankar, C. Spindloe, J. Larour, M. Kozlova, R. Rodriguez, J. M. Gil, G. Espinosa, P. Velarde, and C. Danson, “Counterpropagating radiative shock experiments on the orion laser,” *Phys. Rev. Lett.* **119**, 055001 (2017).
- ³²T. Vinci, M. Koenig, A. Benuzzi-Mounaix, C. Michaut, L. Boireau, S. Leygnac, S. Bouquet, O. Peyrusse, and D. Batani, *Phys. Plasmas* **13**, 010702 (2006).
- ³³A. Visco, R. Drake, S. Glenzer, T. Döppner, G. Gregori, D. Froula, and M. Grosskopf, “Measurement of radiative shock properties by x-ray thomson scattering,” *Physical review letters* **108**, 145001 (2012).
- ³⁴L. Boireau, S. Bouquet, C. Michaut, and C. Clique, “Analytical modeling of the steady radiative shock,” in *Journal de Physique IV (Proceedings)*, Vol. 133 (EDP sciences, 2006) pp. 1031–1033.
- ³⁵J. E. Cross, B. Reville, and G. Gregori, “Scaling of magneto-quantum-radiative hydrodynamic equations: from laser-produced plasmas to astrophysics,” *The Astrophysical Journal* **795**, 59 (2014).
- ³⁶D. Mihalas and B. W. Mihalas, *Foundations of radiation hydrodynamics* (Courier Corporation, 2013).
- ³⁷R. Drake, *High-Energy-Density Physics: Fundamentals, Inertial Fusion, And Experimental Astrophysics* (Springer, 2006).
- ³⁸C. Michaut, C. Stehlé, S. Leygnac, T. Lanz, and L. Boireau, “Jump conditions in hypersonic shocks,” *The European Physical Journal D-Atomic, Molecular, Optical and Plasma Physics* **28**, 381–392 (2004).
- ³⁹A. Dizièze, *Astrophysique de laboratoire avec les lasers de haute énergie et de haute puissance: des chocs radiatifs aux jets d'étoiles jeunes*, Ph.D. thesis, Ecole Polytechnique X (2012).
- ⁴⁰D. Salzmann, *Atomic physics in hot plasmas*, Vol. 97 (Oxford University Press on Demand, 1998).
- ⁴¹M. Edwards, A. MacKinnon, J. Zweiback, K. Shigemori, D. Ryutov, A. Rubenchik, K. Keilty, E. Liang, B. Remington, and T. Ditmire, “Investigation of ultrafast laser-driven radiative blast waves,” *Physical Review Letters* **87**, 085004 (2001).
- ⁴²R. G. McClarren, R. P. Drake, J. Morel, and J. P. Holloway, “Theory of radiative shocks in the mixed, optically thick-thin case,” *Physics of Plasmas* **17**, 093301 (2010).
- ⁴³<https://www.lanl.gov/org/ddste/aldsc/theoretical/physics-chemistry-materials/sesame-database.php>.
- ⁴⁴G. P. Schurtz, P. D. Nicolaï, and M. Busquet, “A nonlocal electron conduction model for multidimensional radiation hydrodynamics codes,” *Physics of Plasmas* **7**, 4238–4249 (2000).
- ⁴⁵A. B. Reighard, R. P. Drake, K. D. K., D. J. Kremer, M. Grosskopf, E. C. Harding, D. R. Leibbrandt, S. G. Glendinning, T. S. Perry, B. A. Remington, J. Greenough, J. Knauer, T. Boehly, S. Bouquet, L. Boireau, M. Koenig, and T. Vinci, *Phys. Plasmas* **13**, 082901 (2006).
- ⁴⁶C. Kuranz, H.-S. Park, B. Remington, R. Drake, A. Miles, H. Robey, J. Kilkenny, C. Keane, D. Kalantar, C. Huntington, *et al.*, “Astrophysically relevant radiation hydrodynamics experiment at the national ignition facility,” *Astrophysics and Space Science* **336**, 207–211 (2011).