ON THE ESTIMATION OF TEMPERATURE IN 'MUNROE JETS'

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ABSTRACT

Recently Stettbacher (see reference 5) calculated the temperature of a 'Munroe' jet to be about half a million degrees. This article presents a revised estimate of the temperature in a jet and it is shown that the temperature of the metal in the jet during its flight in air is of the order of several thousand degrees ($\sim$5000°). If, however, two 'fast' jets collide with each other, then there is a possibility of obtaining a temperature of 10^6 to 10^7 degrees.

During the past ten years, the metal jets[1—4] which are squirted from high explosives with metal-lined cavities have received considerable attention from both experimental and theoretical points of view. The exact physical state of the metal in a 'Munroe' jet is still not thoroughly understood. Because of the brief duration, high temperatures and pressures involved, the actual physical conditions in a jet can be best determined, in principle, by optical or spectrographic methods; but these measurements, even when possible, are a difficult experimental task. Recently Gross (reviewed by Stettbacher[5]) calculated the maximum temperature (about half a million degrees) attained in the jet on the basis of Stefan-Boltzmann Law. The author also discussed the jets as a possible means for thermonuclear reactions, and as an evidence of it quoted Fonberg's[6] work of induced radioactivity in different metallic targets, when attacked by high velocity jets. He did not refer to the latter work[7,8] where it was proved beyond doubts that the targets did not show any radioactivity. Stettbacher assumed the jet to be circular one and having a diameter to be 2 cm. This assumption is also not sound as the X-ray flash photography[1] shows the jet to be about 2 mm. in diameter. We felt that his analysis is based on rather crude assumptions and hence thought of presenting a revised estimate of the temperature in the jet.

The calculated kinetic energy[3] of the jet from Pugh's [9] standard shaped charge equipment (Fig. 1 of their paper) comes out to be $.5\times10^{11}$ ergs. The total heat of explosion of the explosive ($\frac{1}{2}$ lb. of cast 50/50 pentolite) was $1{\cdot}4\times10^{13}$ ergs. This indicates that the kinetic energy of the jet/energy of the explosive (call it efficiency*) is about 4 per cent only. Obviously Stettbacher's assumption of taking the total radiation energy of the jet to be equal to the total energy of the explosive is not valid.

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* This is analogous to the efficiency (kinetic energy of the shot at the muzzle/energy of the propellant) of an orthodox gun and recoilless gun, which are 30 per cent and 10 per cent respectively.

Evans and Ubbelohde's[10] experiments on target calorimetry indicated that the rise in temperature was about 15°C. Taking the target to be a masssive one (3 in. dia. × 4 in. height), the total heat evolved in the target could be assessed as 6 k. cals. for shaped charges of 1-3/8 in. calibre. The energy of the jet was also used up in plastic deformation of the target material and setting up of elastic waves in the target. Assuming this energy to be equal to 1 k. cal., the heat evolved in the target comes out to be 7 k. cals. Obviously this gain in heat by the target is equal to the loss of heat by the jet and slug. Taking the mass of liner (weight of jet and slug) to be 15 gm. and specific heat of iron at high temperatures to be $0 \cdot 11$ cal. degree^{-1} gm.^{-1}, the temperature in the jet comes out to be 4250 degrees.

The metallurgical examination of massive cast iron slug,[11] obtained by firing a 6 in. shaped charge having a 45° conical liner, indicated that it had attained a temperature more than 700°C. The deposit of the metal in the jet on the crater surface (observed as a martensitic region)[12] indicated that the metal in the jet had definitely attained a temperature more than Ac_3 (780°C) point. The order of temperature holds good only if the phase-diagram of iron is considered at atmospheric pressure.

The data on the variation of these critical temperatures on the pressure is not known, however, it is safe to presume that these critical temperatures might increase by even 3 to 5 times at the pressures existing in the jet. This indicates that the temperature of the metal in the jet may be of the order of several thousand degrees ($\backsim$5000°C) only.

Holtgreven[13] took the spectra of jets squirted from high explosive charges with iron lined cavities. The temperature of the liner in flight was estimated from the spectrum and found to be 4400°C. Recently Singh et al.[14] took spectra of iron and copper jets during their flight in air. The copper jet spectrum consisted of emission lines and absorption bands superimposed on a background of continuous emission. The lines were found to belong to the vapour of the metal in the jet. Only a continuum was recorded for the steel jets. Ionised lines of steel and copper were not recorded in the respective spectra. These preliminary spectrographic studies indicated that the metal in the jet is partly in the vapour state and partly in the form of small incandescent fragments. A rough estimation of the temperature in the jet from the intensities of copper lines comes to be about 5000°C. Moreover the absence of ionisation of the atoms in the jet as indicated by these spectra show that the temperature of the metal in the jet is about several thousand degrees only and not several hundred thousand degrees as given by Stettbacher.

It would be of interest to estimate the temperature in the jet from an entirely different point of view. Let us consider two similar jets travelling in opposite directions and colliding with each other. Their kinetic energy is thus concentrated into heat. Assuming that the colliding material effectively behaves as a mono-atomic gas, it would be equal to $\frac{3}{2}\frac{R}{A}T$ where R is the universal gas constant ($R = 8 \cdot 3 \times 10^7$ ergs per degree) and A the atomic weight. The kinetic energy per unit mass of the jet is $2 \cdot 6 \times 10^{11}$ ergs/gm. taking velocity of jet to be 7·2 km./sec. When two such jets collide, their energy is equal to $\frac{3}{2}\frac{R}{A}T$ and taking A=1, the calculated temperature $T=5\cdot2\times10^{11}/(1\cdot5\times 8\cdot3\times10^{7})$ is 4000 degrees.

Recently Koski et al.[15] obtained fast jets in vacuum (say, pressure less than 10^{-5} mm. of Hg) from the collapse of cylindrical liners by means of converging detonation waves in large cylindrical charges. Velocities as high as 90 km./sec. were observed for beryllium jets, with heavier elements exhibiting lower velocities in inverse order of their atomic weights (velocity for lead jets=46 km./sec.). The kinetic energy per unit mass of the jet is $\frac{1}{2}\varepsilon^{2}10^{14}$ ergs/gm. where ε is equal to 1 for beryllium and $\frac{1}{2}$ for lead jets. If two similar jets travelling in opposite directions collide with each other, their kinetic energy is concentrated into heat. Assuming that the colliding material effectively behaves as mono-atomic gas, it would be equal to $\frac{3}{2}\frac{R}{A}T$ where R is the universal gas constant and A the atomic weight. Taking A to be 1 for hydrogen, the calculated T is of the order of 8×10^{5} deg. For lithium deutride, LiH^{2}, taking A=8, $\varepsilon=1$ the calculated T is of the order of 6×10^{6} deg.

These calculations show that the temperature of the metal in the jet during its flight in air is of the order of several thousand degrees (~5000°) only and not several hundred thousand degrees as given by S etbacher. If, however, two fast jets in vacuum collide with each other, then there is a possibility of obtaining a temperature of the order of 10^{6} to 10^{7} degrees. These are interesting temperatures from the point of view of thermonuclear reactions.

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