thermodynamic energy balance that in filling process into a closed vessel, the temperature in the chamber may increase by almost the ratio of specific heats, i.e. $\gamma \cdot T_0$, where T_0 is the temperature of the hot ignitor gases flowing into the vessel. Also in our unsteady flow problem, because of the finite delay time to ignite success portions of the propellant, as the hot propellant gases are generated from the burning propellant, they are compressed and expanded locally depending upon the total (time-dependent) flow and local pressure gradients. One might think of an unsteady piston compression and expansion of the gases which may do local work and heat up the gases even more. And also we never reported such excessively high temperatures as mentioned in the Comment [1].

The second part of the comment deals with the predictions of the extremely low gas temperatures at later portions in the bed. We agree that these values are sometimes unrealistically low. They are the consequence of the large gas velocities and the resultant high kinetic energy of the gases. The complicated relations coupling the gas phase to the particle phase are due in part to viscous drag and convective heat-transfer interaction, which have been extrapolated from low speed, low pressure steady state correlations over inert particles. It may be that these correlations are not valid for the flow conditions at hand. Subsequent work to that reported in [2] has shown us that our predictions, as expected, are quite sensitive to the semi-empirical constants that one uses in these constitutive relations. For example, a 25"% increase in the drag coefficient calculated from the Ergun relation reduces the gas velocities enough to prevent the predictions of such low temperatures as presented in the Appendix of [2].

Regarding the situation of having particle temperatures increase while at the same time allowing the surrounding suspending gas temperatures to decrease should really be no cause for alarm. Our model [2] utilizes an independent solid-phase energy equation. When written in operator-form one can see that the substantial derivative of the particle energy can change for reasons other than simply a convective heat transfer from the gas. But Nelson's comment here does raise an important issue, namely when deriving the conservation equations we (and most other investigators) assume that the solid-phase, although dispersed, represents a continuum. The net result is that the particles in many ways act like a gaseous medium. Thus a rapid deceleration

of the particles locally could result in an increase in particle temperature. It is probably for this reason that one phase increases in temperature while the other phase, obeying its own conservation equation might decrease. It seems natural that additional work needs to be carried out to adequately explain such phenomena to the satisfaction of all.

A final query made by Nelson was in regard to the predicted bed porosity, ϕ, during the transients. Here, solids loadings, defined as $(1-\phi)$ were predicted to be as large as 75"% in some portion of the bed. Nelson is correct that such high loadings would result in a normal axial stress which would resist this and further compaction of the propellant grains. Since we had not included a constitutive relation for the solid mechanics of an aggregate under dynamic loading, we had arbitrarily cut off our calculations below this porosity value. However, Nelson is probably not correct when he states that the cut-off should be no lower than $\phi \sim 0.40$.

It must be remembered that the grains near the ignitor have been burning at high rates long enough to reduce their volume, so that the compaction of these smaller grains into the larger, some unignited grains, can result in a greater solids loading. Of course, for the problem presented, very little of the grain has burned away to change the grain sizes appreciably. And so the comment made by Nelson is a good one, in the sense that the model should have included a particle particle interaction to prevent the high compactions we reported.

Finally, the errata as pointed out in the last paragraph of [1] is appreciated.

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THE EFFECT OF SURFACE THERMAL CONDUCTIVITY ON DROPWISE CONDENSATION HEAT TRANSFER

THE FACT that, during dropwise condensation, some parts of the condensing surface are essentially adiabatic (those covered by large drops) while other parts carry an extremely high heat flux, should give rise to an effective thermal resistance—the so-called "constriction resistance" Hannemann and Mikic have recently put forward a theory [1] for the constriction resistance which indicates that the effective vapour-side heat-transfer coefficient for dropwise condensation depends on the thermal conductivity of the condenser material. In support of their theoretical result these authors cite their own [2] and two earlier experimental studies [3, 4], while explanations are offered for conflicting evidence that the thermal conductivity has insignificant effect [5–7]. These comparisons warrant more detailed consideration.

A significant difference between those earlier measurements which, for metallic surfaces, indicate a dependence of heat-transfer coefficient on condenser material [3, 4] and that which suggests the contrary [7], is the fact that in the latter,

the steel surface was thinly copper-plated (plating thickness 12 μm) to ensure effectiveness of the promoter. Leaving aside for the moment the question of the relative accuracy of these data, and in view of the well-known difficulty in establishing ideal dropwise condensation on most non-copper-containing surfaces, it is possible that the observed dependence on condenser material [3, 4] might have been due to variations in promoter effectiveness on the different materials rather than to their thermal conductivities.

On the question of accuracy of the earlier measurements, Tanner et al. [3] and Aksan and Rose [7] both measured the condensing surface temperature by extrapolation from temperatures indicated by thermocouples located at different distances from the condensing surface. The probable error in the surface temperature, arising from uncertainty in the positions to which the observed temperatures relate, has been analysed by Wilcox and Rohsenow [8] and, for fixed positions of the thermocouples, shown to be systematic,
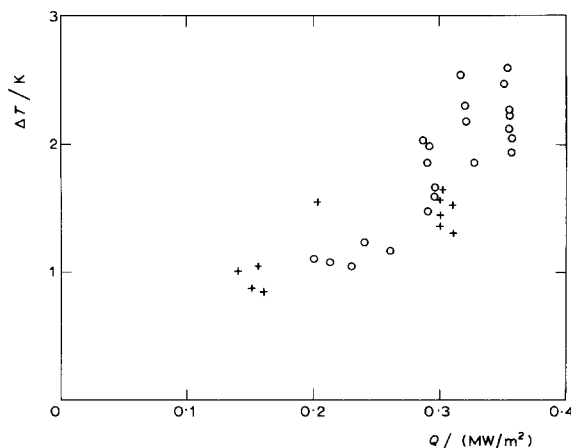
FIG. 1. Dependence of vapour-to-surface temperature difference, ΔT on heat flux, Q: +, copper (data of [7]); $\bigcirc$, steel, (values of ΔT from [7] have been *increased* to illustrate maximum reduction in heat-transfer coefficient through systematic error in surface temperature—see text).

inversely proportional to the thermal conductivity of the condenser material, and proportional to the heat flux.

For the thermocouple hole sizes and positions used in [7] the possible error (calculated according to [8]) in the surface temperature of the steel plate varied from about 0.3 K at the lowest heat flux to about 0.6 K at the highest heat flux. In Fig. 1 corresponding values have been *added* (for the steel plate) to the observed vapour-to-surface temperature differences. It is clear that even when all of the error is assumed to be in the direction which would lead to lower heat -transfer coefficients (as required by the theory of Hannemann and Mikic [1]), the results for steel and copper are not widely different. The probability that the error in the vapour-to-surface temperature difference could have been as large as was suggested in [2] is very low. On this point it should be mentioned that the error estimate [8] in the surface temperature is the standard deviation (based on a truncated normal distribution of probability of thermocouple position* within a hole) on the surface temperature found by extrapolation. The figures quoted above are probably overestimates since the side of the square holes used in [7] was taken as the *radius* of an equivalent round hole.

The measurements of Tanner *et al.* [3] were for lower heat fluxes and correspondingly lower values of vapour-to-surface temperature difference. The calculated possible systematic error in the temperature of the steel surface, for the maximum heat flux is quoted in [2], as 0.5 K while the observed vapour-to-surface temperature difference was only 0.7 K. Evidently, the heat-transfer coefficients for steel reported in [3] are more susceptible to this form of error than those of [7].

The vapour-side heat-transfer coefficients [4] were inferred from overall heat-transfer measurements and, in view of the relatively low-vapour-side resistance, are prone to large errors.

The fact that the heat-transfer coefficient for dropwise condensation of steam on PTFE is essentially the same as that on copper [5, 6], while the thermal conductivity of PTFE is less than that of copper by a factor of about 1500, was

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* The position to which the measured temperature relates.

explained in [2] by the thinness of the PTFE layers used in the measurements (1.5 μm in [6] and 10 μm in [5]). It should however be bourne in mind that these thicknesses are thermally equivalent to about 2 and 15 mm of copper.

In conclusion, it seems reasonable to expect that there should be a constriction resistance and that, in consequence, the effective vapour-to-surface heat-transfer coefficient should depend on the conductivity of the surface material. However, at present the only data apparently free both from excessive error in surface temperature measurement and from the possibility of surface chemistry effects, are the conflicting results of [2] and [7], the former supported by theory [1] and the latter by the results for PTFE [5, 6].

A possible explanation for the absence of a dependence of heat-transfer coefficient on the conductivity of the material of the condensing surface (if this should, in fact, prove to be the case) might lie in the fact that, owing to the extremely high coalescence rate, the surface temperature is essentially uniform. Peterson and Westwater [9] have observed as many as 400 000 coalescences in the process of the formation of a drop of radius about 1 mm. Such an event takes place, typically, in around one second. Thus, on a square centimetre of surface, coalescences can occur with a frequency of about 10^7 per second.

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