JOURNAL OF COMPUTATIONAL PHYSICS 49, 349–350 (1983)

Letter to the Editors

Reply to Kansa's Remarks on the Efficiency of ICE-Like Schemes for Combustion Problems*

A recent article by Kansa [1] contains some misleading statements about the APACHE code [2] and about the suitability of ICE-like schemes [3, 4] for combustion problems with large chemical heat release. We hope the following comments will serve to correct any misconceptions that may have resulted.

In Section II, Kansa states, "One of the primary disadvantages of the APACHE code is that the iteration scheme is terminated after an upper iteration bound is reached whether or not convergence is achieved." This statement rather disingenuously suggests that such an arbitrary termination is a basic feature of our numerical method and is exercised under normal operation. In reality, however, the upper bound mentioned serves merely as a "safety valve" to conserve computer time if for some reason the iteration fails to converge normally. (It is, of course, prudent and customary to include such a safety feature in the implementation of any iterative procedure.) The upper bound in APACHE is arbitrarily set at 500, but a value of 100 might equally well have been chosen; the bound merely needs to be well above any normal or reasonable iteration number. (The meaning of "normal or reasonable" is of course problem-dependent, but as a rule of thumb we regard the iteration number as excessive if it systematically exceeds about 50.) Needless to say, the arbitrary bound of 500 is never even remotely approached under normal conditions, and obviously does not constitute a "disadvantage" of APACHE.

In Section VII, Kansa claims that in [2] we "... state that in problems with large amounts of heat release, 500 or more iterations per time step may be required for convergence, if indeed it occurs at all." We made no such statement in [2] or anywhere else. We did, however, caution the potential user that APACHE tends to be inefficient in problems with low Mach number and large heat release. (It was developed primarily for chemical laser applications, where the flow is usually transonic or supersonic.) In such problems the average number of iterations per time step may be large enough that it becomes advantageous to run APACHE in its purely explicit mode instead of its ICE-like mode. This transition typically occurs at iteration numbers much closer to 50 than to 500.

Of course, purely explicit calculations are themselves inefficient for problems with low Mach number and large heat release, and we do not recommend the existing

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0021-9991/83/020349–02$03.00/0

version of APACHE [2] for such problems. It must be emphasized, however, that the inefficiency of APACHE in such problems is a peculiarity of the particular variant of ICE that it employs, and is *not* an inherent characteristic of all ICE-like schemes. As we have remarked elsewhere [5], the difficulty in question can be avoided by positioning the (explicit) energy calculation at the beginning of the computational cycle; the effect of the chemical heat release is then included in the pressure iteration on the current time step. (This effect, however, must *not* be allowed to contribute in the *explicit* part of the momentum calculation, a caveat that was not mentioned in [5].) We use this procedure in the CONCHAS [6] and CONCHAS–SPRAY [7] codes, which were developed primarily for application to the low-speed highly exothermic flows in internal combustion engine cylinders. The procedure works well and iteration numbers are not excessive. The same procedure could be implemented in APACHE with relatively minor modifications, but we have had no occasion to do so. We would be glad to supply interested readers with an outline of these modifications.

Kansa goes on in Section VII to estimate the computational efficiency of his scheme as compared with other schemes, and in particular with ICE-like schemes. In a presumably typical example, he estimates that each iteration in his method is computationally equivalent to about 125 ICE-like iterations. In order to conclude that his scheme is slightly more efficient than ICE-like schemes, he finds it necessary to assume that the latter will have an average iteration number of 500. Even if this assumption were valid, the ICE-like schemes would still have the considerable advantage of much greater simplicity. In reality, of course, iteration numbers of perhaps 25 are much more typical of appropriately formulated ICE-like schemes.

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RECEIVED: January 8, 1982

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