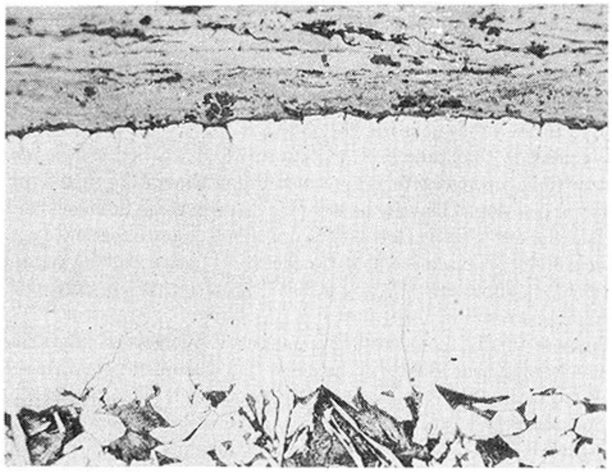

Fig. 9 Photomicrograph of alonized carbon steel exposed at 1600°F (870°C) in the entrained bed for 50 hr (200×)

from the 50-hr exposure at 1600°F (870°C) in the entrained bed of the combustor. Although very little of the Alonized coating has been converted to oxide, there are fingers of penetration suggesting that internal oxidation extends to a depth of about 0.5 mils (13 μm). This is nearly the same amount that was determined by weight loss analysis on the Alonized shoe, although the shoe operated at a much lower temperature. The Alonized coating did not appear to be attacked on the bottom surface as did the stainless steel, except at one location where the coating was very thin.

Discussion

These erosion-corrosion investigations have demonstrated that the life of heat exchange tubes to be incorporated in the multisolids fast fluidized-bed combustor will depend primarily upon erosion, which was more severe in the dense bed than in the entrained bed. The severity of erosion in the dense bed (greater than 100 mils/yr, 2540 μm/yr) was sufficient to reject designs for incorporating heat exchanger tubes in this location. In the entrained bed, however, the erosion was found to depend upon the orientation of the tubular specimens. The total metal wastage (about 4 mils/yr, 102 μm/yr) was less than that for air oxidation when the specimens were parallel to the flow direction, but increased to about 60 mils/yr, (1524 μm/yr) on specimens mounted perpendicular to the flow of particles. Hence in the entrained bed, erosion would indicate the need for a special material and/or protective shoes for heat exchanger tubes that are not parallel to the flow.

The analysis of shoe material and design has demonstrated that the shoe can create a turbulence in the flow which can erode unprotected portions of the tube. Hence a streamlined design or complete coverage of the heat exchanger tube may be required. Of the shoe alloys evaluated, the Type 347 stainless steel exhibited the least attack, while the E-Brite and RA333 were somewhat less resistant to erosion. However, the latter two alloys reacted with the FeS particles deposited on the shoe during Run 1006. These particles were not observed in other experiments. The Alonized carbon steel shoe did not appear to have been eroded, but did form an adherent oxide coating. Although removal of this oxide resulted in a somewhat higher weight loss than occurred with the other shoe materials, it is possible that the oxide coating would be protective and the metal wastage rate would decrease significantly with longer exposure time. If this proved to be the case, the use of Alonized carbon steel tubes for heat exchangers would be more satisfactory than attaching protective shoe materials. It will be important, however, to establish the long-term performance of the Alonized carbon steel.

Materials evaluation for high temperature (1600°F, 870°C) uses, such as tube supports and walls for the MS-FBC, has indicated that Type 347 stainless steel is superior to the other alloys evaluated. Type 304 is particularly prone to intergranular attack, while E-Brite is pitted severely where FeS particles are deposited. RA333 exhibits internal reaction, growth of a grain boundary phase, plus dealloying at the surface. Type 304, which was evaluated by metallographic section from the laboratory combustor wall, exhibited severe intergranular attack in 500 hr of operation and, therefore, would not appear to be a suitable material for high temperature service in this environment. Although the Alonized carbon steel appears to be resistant to general attack at 1600°F (870°C), there was some evidence for internal reaction to a depth of about 0.5 mil (13 μm) in 50 hr. Here again long time exposures (500–1000 hr) are needed to appropriately evaluate this material. The carbon steel would not have adequate strength at this temperature, but the Alonized coating could be applied to a higher strength alloy.

Conclusions

From the data obtained in this study of erosion-corrosion in the MS-FBC, which for the most part covers 50-hr exposure experiments, the following conclusions can be reached.

1. The combustor environment is less corrosive but more erosive than air, except perhaps when FeS particles are deposited on metal surfaces.
2. The lower corrosivity of the combustor environment can be attributed to the formation of a $CaSO_4$ deposit that protects substrates operating at low (500°F, 260°C) metal temperatures.
3. At high (1600°F, 870°C) metal temperatures sulfidation occurs by reaction of the substrate metal with $CaSO_4$ and/or FeS and corrosion becomes an important factor in metal wastage.
4. Erosion of heat exchanger materials is markedly affected by tube orientation with respect to particle flow direction and location in the combustor, being higher for tubes perpendicular to flow and for tubes in the dense bed.
5. Although Type 347 stainless steel exhibited the least metal wastage by corrosion at high temperature, E-Brite and RA333 exhibited slightly better erosion resistance at low temperature.
6. Erosion was not evident for Alonized A106 and although an adherent corrosion layer did form, the extent of the reaction is expected to diminish with time, and further evaluation is needed.
7. The use of replaceable shoes to protect heat exchanger tubes will require an appropriate design to avoid turbulence and erosion of the uncovered carbon steel tube.

DISCUSSION

L. A. Ruth and M. S. Nutkis[1]

The authors have made a commendable study of erosion and corrosion of boiler tube materials. We would, however, like to make several comments based on our experience with the cooling tubes in our fluidized bed combustion miniplant.

The miniplant is a 32 cm diameter dense bed combustor using limestone or dolomite sorbent (−8 +25 mesh) and superficial gas velocities of 1-2.5 m/s. Cooling tube bundles, consisting of vertically oriented tubes with U-shaped return bends at the top and bottom of each tube, are located in the dense bed. We have not detected any measurable wear on the vertical portions of these tubes (316 SS),

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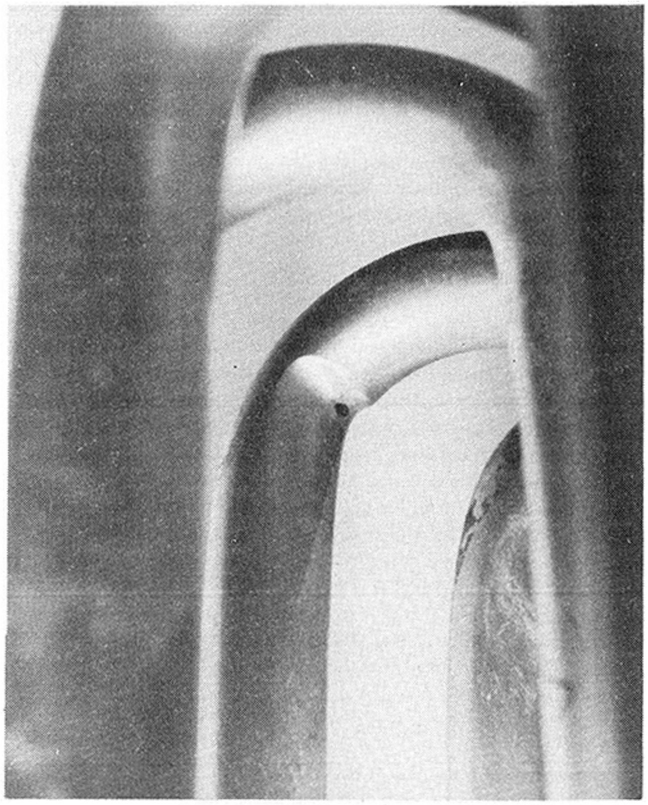

Fig. 10

however there was severe wear due to erosion on the underside of some of the upper U-bends (see Fig. 10). We found that the eroded areas were very localized and that only slight changes in orientation or position of the tubes caused unexpectedly large changes in the extent and location of the tube wear. The erosion was believed to have been caused by annular gas streams flowing at high velocities along the length of the vertical tubes. Bed solids accelerated by the gas stream impinged on the underside of the upper U-bends. We eventually were able to control the erosion by using baffles installed near the U-bends to divert the gas jets. The baffles took the form of semi-circular rings welded to the tubes near the U-bends.

We caution that tube erosion rates in fluidized bed combustors appear to be strongly affected by even minor changes in tube orientation or position. This may be especially true in small fluidized beds, such as the one used by Battelle (15 cm). Thus, more experience with erosion in larger units seems to be necessary before making general conclusions about the efficacy of heat transfer tubes in dense bed fluidized bed combustors.

We note, finally, that the authors compare erosion rates in the dense and entrained beds. Solids in the dense bed (hematite) are different from solids in the entrained bed (cement sand) in both size and composition. These differences may have been partly responsible for the variation in erosion rates between beds.

Authors' Closure

The comments by Mssrs. Ruth and Nutkis are very pertinent to heat exchanger design in fluidized beds. Since the presentation of this paper, we have had the opportunity to make some similar erosion-corrosion exposures in a 14 × 25 in. (35.5 × 63.5 cm) version of the multisolids fluidized bed combustor. We noted that erosive effects were significant even on vertical tubes where the particle flow changed direction in the entrained bed. Each combustor design will have to be examined carefully to determine the vulnerable points, and erosion protection provided as necessary.

Because the velocities in the dense and entrained beds are practically the same, the difference in erosion encountered in the two zones must be the result of particle concentrations and types of material.