Validity of physical flow modeling of kraft recovery boilers

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ABSTRACT: A new air system failed because its primary air jets did not control the char bed effectively. The problem could not be predicted from physical flow modeling.

KEYWORDS: Air, cameras, flow, flow measurement, gas flow, models, operations, performance evaluation, physical tests, recovery furnaces.

Physical flow modeling and mathematical modeling are complementary procedures for evaluating gas flow patterns in kraft recovery boilers. Both of these methods can provide windows into the actual flow conditions in operating boilers. The two methods offer somewhat different views. Although neither view is entirely clear or complete, each provides useful information. Both procedures have a place in investigating promising techniques for changing the fluid flow patterns to improve boiler performance.

Here, we compare physical modeling results to results of cold-flow air tests on a full-scale boiler and to camera observations in the operating boiler, for three distinctly different gas flow patterns. The comparisons illustrate the validity of physical flow modeling as well as some of its limitations.

Basic concepts

Critical limitation

The main factors on which criteria for recovery boiler performance are based include:

- Safety
- Atmospheric emissions
- Capacity
- Reduction efficiency.

Interaction of the gas flow and the liquor particles, both in flight and on the surface of the char bed, has an influence on these factors. Physical flow modeling does not account for this interaction in any way. The effect can be evaluated to some extent in mathematical modeling, though not reliably. In the end, boiler trials under operating conditions are required to test proposed changes in fluid flow patterns and liquor spraying procedures. Nonetheless, physical flow modeling and mathematical modeling can be used to identify promising concepts to be tested in boiler trials.

Combustion effects

Aerodynamics establishes the gross flow pattern; combustion does not alter the pattern—it just accentuates it (*1—3*). The basic flow patterns apparent in cold-flow testing are maintained when combustion occurs, although the flow velocities are greater and the area of influence may be extended. If there is a specific gross flow pattern in a physical model during cold-flow testing, there will be a similar gross flow pattern in the actual boiler with combustion, provided some care is taken to establish similarity between the physical model and the actual boiler.

Validating physical modeling results

We at Sandwell used two simple techniques for checking the validity of physical flow modeling results (*1, 2*):

1. Cold-flow air tests on the full-scale boiler
2. Camera observations in the operating boiler.

Methodology

In 1987, a physical model of the vintage Combustion Engineering recovery boiler at Celgar Pulp Co. was constructed at 1/12th scale (*1, 2*). The air ports were also at 1/12th scale, not enlarged.

Both water and air were used as working fluids. The use of water with a tracer made it possible to examine flow. The stream lines and flow patterns could be observed directly, permitting a qualitative assessment.

During air tests, quantitative measurements of flow velocity were made, using a hot-wire anemometer. The anemometer indicated the speed of the flow but not the direction. Attempts

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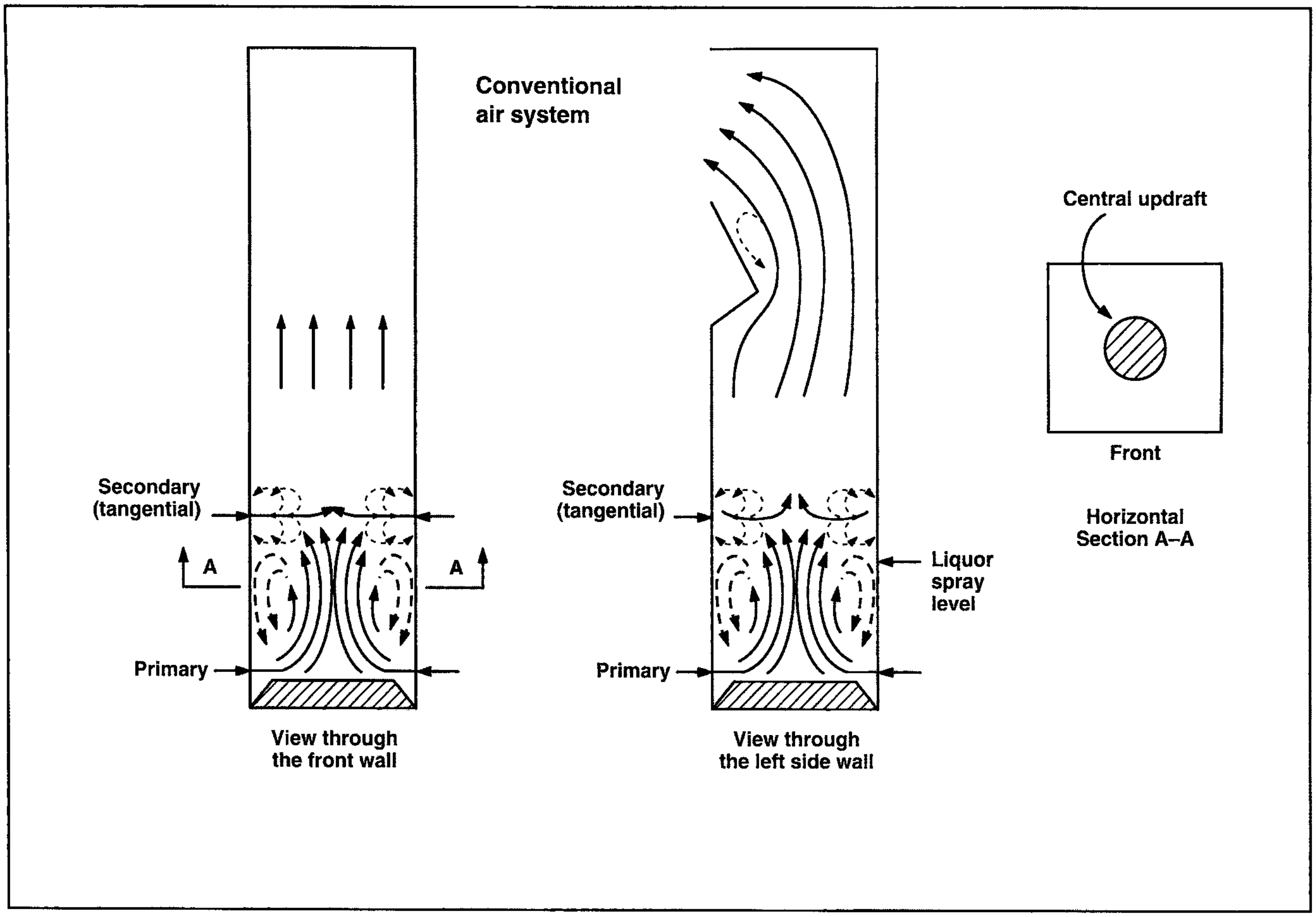
1. For the conventional air system with primary air entering from four walls, the water tests on the physical model showed a chimney flow pattern, or a central updraft with a downward flow near the walls.



were made to evaluate the direction of the flow in the model using streamer tapes and flaps of balsa wood, but these approaches were not successful. The assessment of flow direction during air tests was based on the results of flow observation during the water tests.

Cold-flow air tests were conducted on the Celgar boiler itself. In these tests, ambient air was added to the boiler through the air ports at normal operating flow rates. Other than this air flow, the boiler was not operating. A hot-wire anemometer was used to measure the speed of the vertical flow component at various positions in the boiler.

Special cameras were used to observe the flow patterns in the actual boiler during operation, including conventional char bed cameras, a portable camera with a right-angled lens, and a particulate-counting camera at the furnace exit.

Air system evaluations

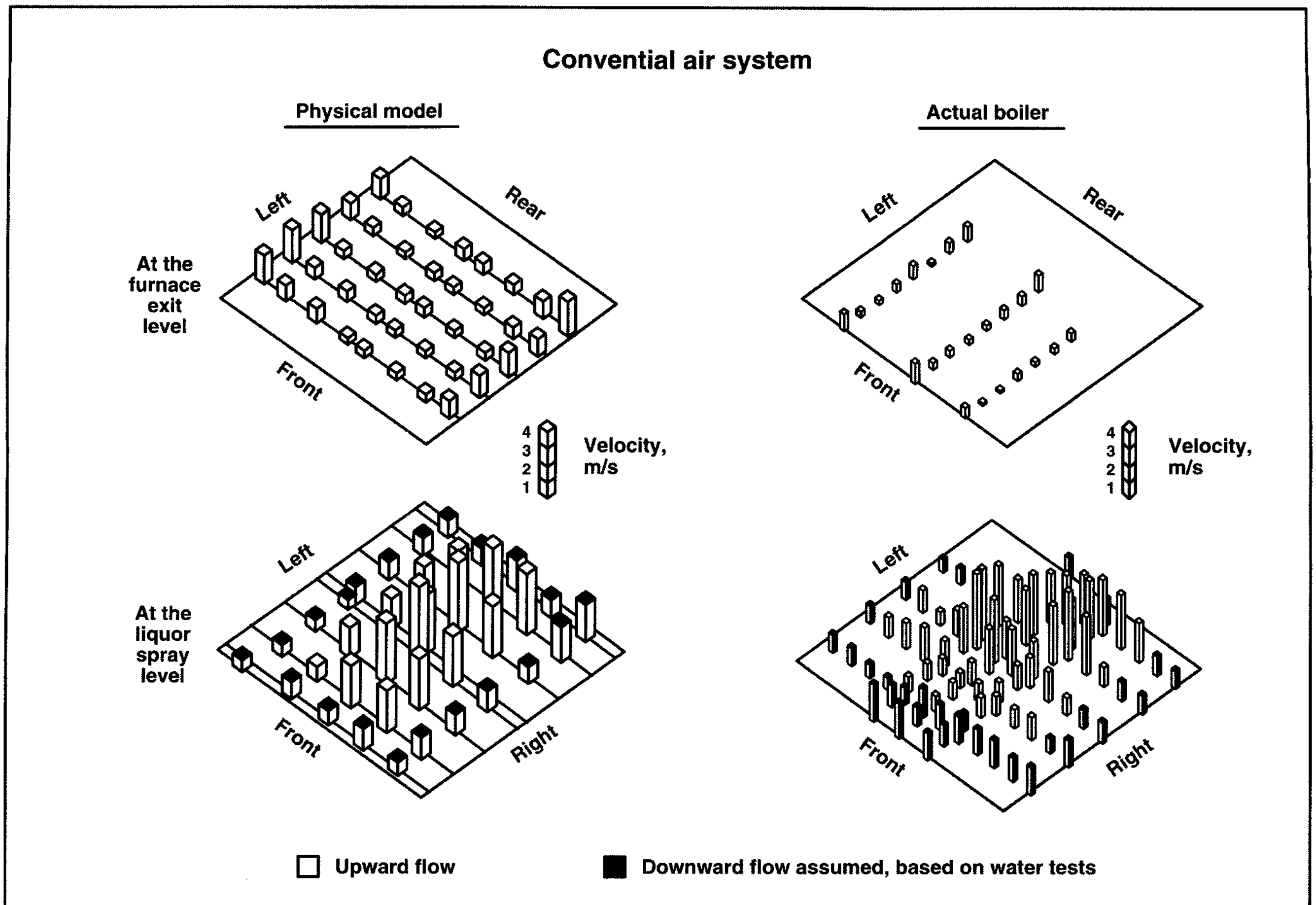
Three air systems were examined:

1. A conventional Combustion Engineering system, with two air levels. The primary air was fed more-or-less uniformly through all four walls. Above the liquor spray level, secondary air was added in a tangential arrangement.
2. Two-wall primary air (*4*). The primary air was restricted to two opposing walls, with the secondary air in the conventional tangential pattern.
3. A novel air system having three air levels (*5*). The primary air ports were enlarged to provide low-velocity primary jets. A second air level was added below the liquor spray level, using low-velocity jets from the front and rear walls, in a partially interlaced pattern (*4*). The air level above the liquor guns was modified to a two-wall, fully interlaced system, with the jets oriented downward at 30°.

Conventioanl air system

The results of water tests on the physical model are displayed in **Fig. 1**. There was a chimney flow pattern in the lower furnace, with a core of higher velocities up the center of the furnace and a downward flow near the walls. At the furnace exit, just below the bullnose, the flow was generally slow and uniform, with little turbulence. At this elevation, the flow was evenly distributed across the horizontal cross section, and

2. For the conventional air system, these velocity profiles on horizontal grids show the results of the air tests on the physical model (left) and on the actual boiler (right).



velocities were significantly lower than in the lower furnace. At the furnace exit, there was a remnant of the clockwise horizontal swirl imparted by the tangentially oriented secondary jets.

The air test results from the model are summarized in **Fig. 2**. The results are largely consistent with the water test results.

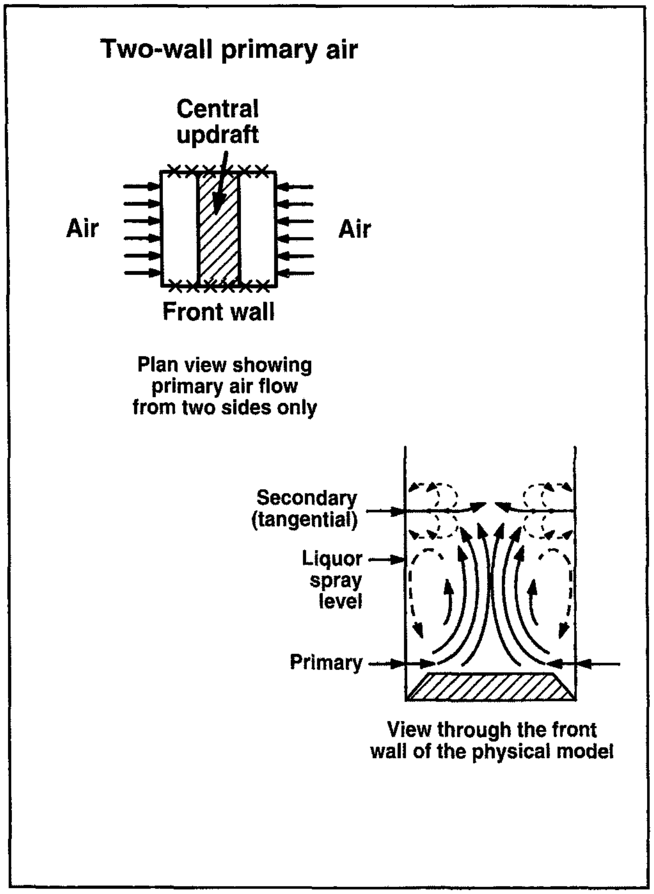
Figure 2 also provides the results of the cold-flow air tests on the actual boiler. These results are similar to those obtained in air tests on the physical flow model. In the boiler, the position of the chimney on the horizontal cross section at the liquor spray level was skewed toward the right rear corner because the primary air supply to all four walls was not uniform. The front wall and left wall of the boiler tended to receive more primary air than the rear wall and right wall (where the front wall is the wall opposite the bullnose). The gustiness of the flow in the boiler was at least twice as great as in the model (*1, 2*).

During the operation of the boiler, the chimney flow pattern was evident in the images from two char bed TV cameras in the lower furnace. The sweep of the primary jets across the char bed was apparent, as were their upward turns near the center of the furnace. There was a noticeable downward flow of gases near the furnace walls; it appeared that this downflow was being sucked into the primary jets. Similar observations can be made with the char-bed imaging cameras in most recovery boilers.

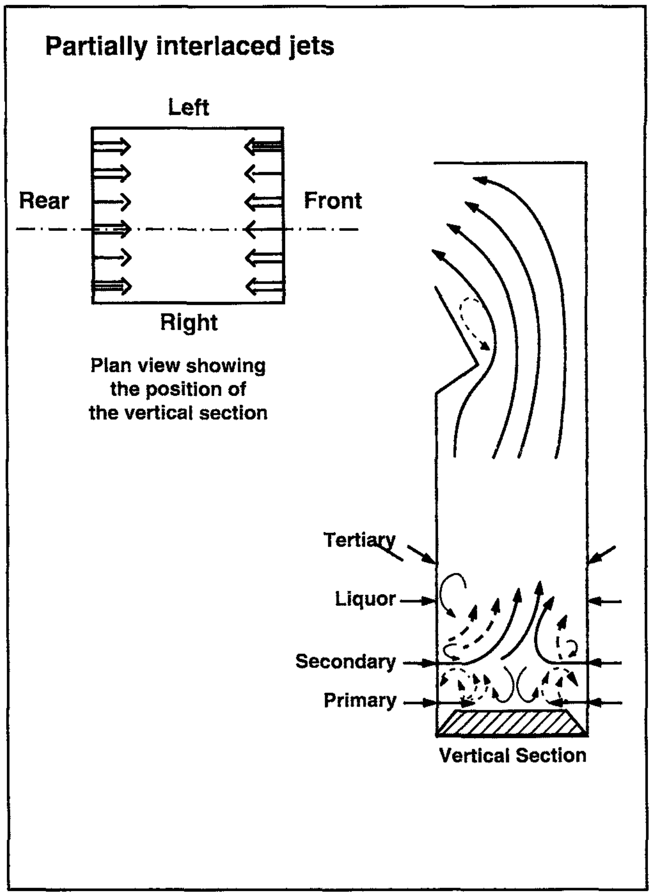
A special camera fixed with a right-angled lens was used in the boiler to look down into the lower furnace from the furnace exit level. (A short video prepared on this work is available from Sandwell.) With this special camera, it was observed that the central region of the horizontal cross section of the lower furnace had high upward velocities and considerable turbulence, whereas the regions near the walls had less turbulence. The tangential secondary air jets, above the liquor spray level, were barely visible.

The area of the higher velocities in the center of the furnace seemed to extend upward somewhat above the upper air level, though not significantly so. The core of high velocities moved around erratically in a region covering approximately the center third of the horizontal cross-sectional area; here, the turbulence was variable and abrupt. The upper part of the chimney tended to have a swirl, as would be expected from the tangentially oriented upper

3. The water tests on the physical model for primary air coming from only two walls showed the chimney section covering one-third of the horizontal cross section.



5. Flow patterns observed during water tests on the physical model for the novel air system with partially interlaced secondary jets

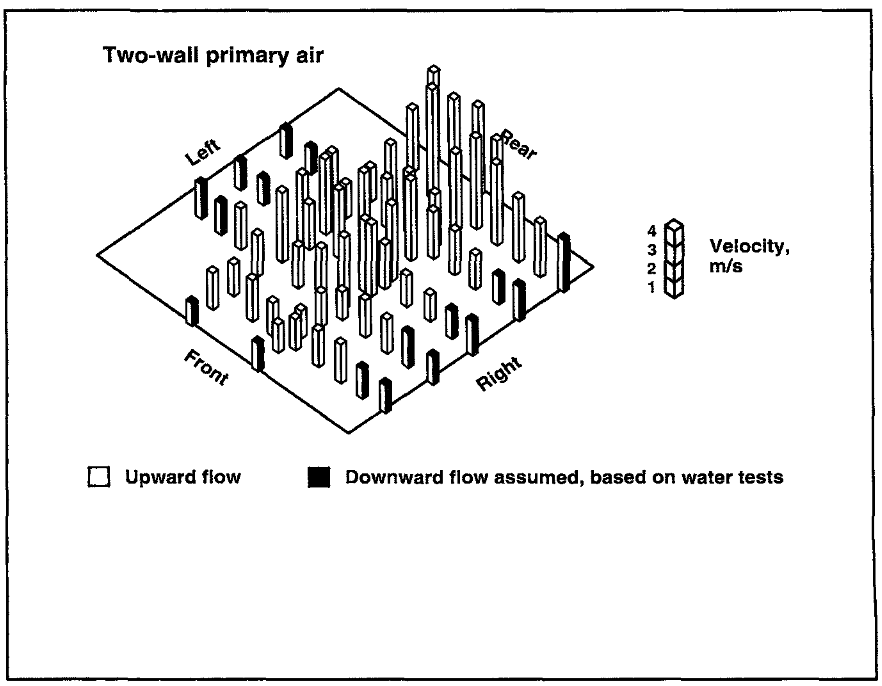


air, but the swirl was not overly pronounced.

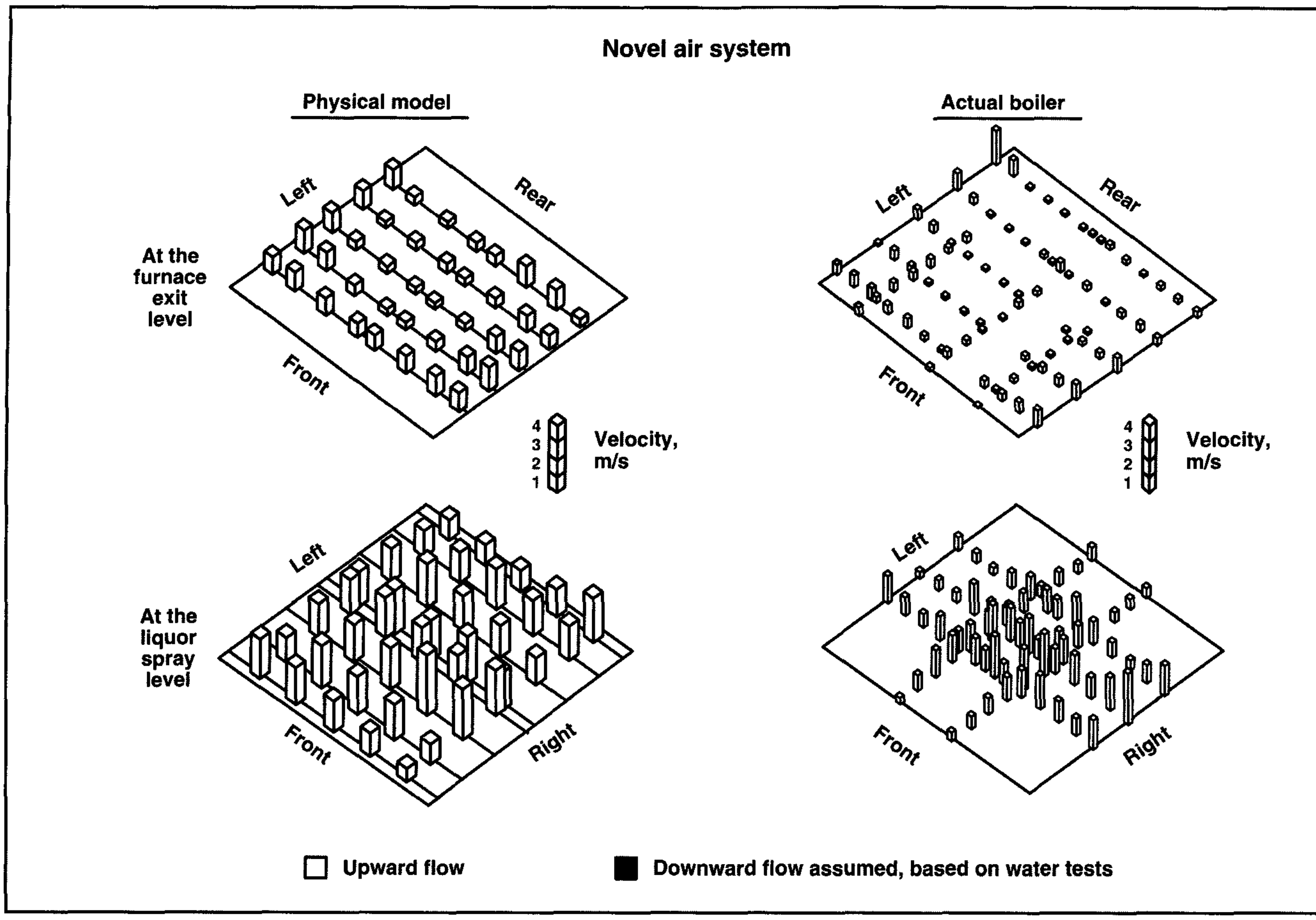
When the same special camera was inserted into the lower furnace through an unused liquor gun port, a downflow of furnace gases was observed near the furnace wall, like the downflow observed in the water tests on the physical model.

A special particulate-counting camera was installed on a trial basis in the Celgar boiler at the furnace exit level using a port in the middle of the front wall. This camera revealed the burning liquor spray particles entrained in the furnace gases. At the furnace exit level, the flow was erratic, with no specific upward component. This finding is contrary to the physical modeling results, which indicated well-developed and uniform upward flow at the furnace exit. However, this camera was focused for a short depth of

4. In cold-flow air tests on the actual boiler using two-wall primary air, the velocity profiles at the liquor spray level showed the central band of higher velocities skewed toward the rear wall.



6. For the novel air system, these velocity profiles on horizontal grids show the results of the air tests on the physical model (left) and on the actual boiler (right).



field at the time, so that it showed mainly the region near the furnace wall, extending, say, three feet into the furnace. When the special camera with a right-angled lens was inserted into the boiler at the same elevation and turned upward to look into the lower part of the screen tubes, the flow was observed to be quite well developed and uniformly upward; however, the flow was gusty.

Subsequently, the special particulate-counting camera was installed in the boiler on a permanent basis, looking to the boiler through a port in the center of the front wall about halfway up the screen tubes. There, the flow was uniformly straight upward.

Generally, camera observations of the movement of particles in the gas in the actual boiler were consistent with the gross fluid flow patterns observed in the physical flow model.

Two-wall primary air

In the physical model, the windboxes serving the primary ports on the front and rear walls were dampered off, so the total primary flow originated from the two side walls only. The results of water tests are illustrated in **Fig. 3**. A chimney was evident in the lower furnace, but the region of upward velocities was spread out from the front wall to the rear wall, covering about a third of the horizontal cross section of the furnace. The area of the chimney was three times larger than with primary air from all four walls.

The upward velocities in the chimney were lower than with conventional operation with four-wall primary air. There was a downward flow of fluid near the left and right walls, but the downflow was not as extensive or as strong as with four-wall primary air. The height of the chimney was not altered noticeably by the change to two-wall primary operation, even though the velocity of the jets from the primary ports remaining in use was basically doubled.

No air tests were done on the physical model for two-wall primary air.

A cold-flow air test was conducted on the boiler. The results are summarized in **Fig. 4**. (The test conditions for the air system were the same as those used during an associated five-week, two-wall primary air trial.) The dampers for the windboxes for the primary ports were fully opened on the left and right walls and were fully closed on the rear walls. The dampers on the front wall, where the smelt spouts were located, were partially open.

The velocity profile at the liquor spray level was consistent with observations made in the physical model during water tests. In the boiler, there was a band of higher velocities that extended from the front wall to the rear wall, covering the middle-third region between the two side walls. The chimney of higher velocities was skewed toward the rear wall, however, because some of the primary air was admitted to the furnace through the front wall.

A five-week trial was conducted on the boiler, as mentioned, using the two-wall primary air concept. Two-wall primary air provided a char bed that was flatter and easier to control than it was with four-wall primary air. The bed had a central small ridge that extended almost all across the boiler from the front wall to the rear wall. The char bed cameras showed a central region of upward flow, with downflow regions near the front and rear walls, similar to the gross flow pattern observed in the physical model.

Subsequent trials on another boiler demonstrated that two-wall primary air decreases the formation of fireside deposits on the pendent heating surfaces in the upper part of the boiler, thereby increasing boiler capacity (*6*). Also, temperatures in the lower furnace were increased by 60°C, suggesting improved gas mixing (*6*). These improvements—the improved char bed control, the decreased plugging rate, and the increased temperature in the lower furnace—could not be demonstrated by physical flow modeling.

Partially interlaced jets

Figure 5 illustrates part of the flow patterns observed during water tests on the physical model with partially interlaced jets. Viewed from the right side of the physical model, the figure shows a vertical section through one opposing set of partially interlaced secondary jets. This vertical section is at a position, partway between the right wall and the left wall, where a larger jet from two ports on the rear wall opposed a smaller jet from one port on the front wall. These two jets met about midway between the two walls. There, the moving fluid was deflected more or less at right angles, mostly upward but some downward.

The upflowing fluid formed a small chimney occupying a space between the midpoint and the point two thirds of the way from the rear to the front. The position of the chimney and the direction of flow in the chimney, somewhat toward the front wall, resulted from the dominance of the larger jet from the rear wall over the smaller jet from the front wall.

The chimney persisted to a height of about the tertiary air level. The pattern created by the secondary jets included slight downward flows near the front and rear walls, but these downflows were much weaker than the downward flows associated with the lower furnace chimney of the conventional air system.

Where there was one secondary port on the rear wall opposed by two secondary ports on the front wall (not shown), the observed flow pattern was the reverse of that in Fig. 5—the chimney tended to be biased toward the rear wall rather than the front wall.

The primary jets were slower than the secondary jets; as a result, conditions at the secondary level were more turbulent than at the primary level. However, the velocity extremes in the chimney formed by the secondary jets were lower than the velocity extremes in the chimney associated with the conventional air system. Generally, the flow patterns associated with the primary jets were somewhat diffuse and were difficult to see at first. Overall, the results of physical flow modeling confirmed the validity of the design concept of creating less turbulence in the lower furnace. The intent of this feature was to decrease the carryover of liquor spray particles.

Above the tertiary air level, the turbulence decreased markedly. At the furnace exit, the flow was uniform and straight upwards, with little turbulence. With the fully interlaced tertiary jets, the flow at the furnace exit did not have a horizontal swirl component, as was evident with the conventional tangential air system. Like the conventional air system, velocities at the furnace exit were much lower than in the lower furnace. The well-developed flow continued into the upper heating surfaces. Generally, there was very little mixing above the tertiary air level.

The results of air tests on the physical flow model are summarized in **Fig. 6**. The velocity profile at the liquor spray level was relatively uniform, with no specific areas of higher velocities. The six sets of partially interlaced jets provided six minor chimneys that tended to blend into each other, rather than the single accentuated chimney with the conventional air system. The velocity profile at the furnace exit was much the same as for the conventional air system.

Figure 6 also shows the results of the cold-flow air test on the boiler. The velocity profile is similar to that of the physical model. In the boiler at the liquor spray level, the velocities are reasonably uniform on the horizontal cross section, although there are some higher velocities near the center of the furnace. In the boiler, the novel air system improved the uniformity of the velocity profile, compared to the conventional air system, though not as dramatically as observed in the physical flow model. When the boiler was in operation, the flow in the lower furnace was much less turbulent than for the conventional air system. There was no evidence of a downflow beside the furnace walls. The amount of entrained particles visible in the gas flows in the lower furnace was considerably less than with the conventional air system. The design objective of decreased turbulence in the lower furnace was achieved.

The special camera with the right-angled lens was used to look down into the lower furnace from the furnace exit level. There appeared to be a region of higher velocities covering about one third of the horizontal cross section and extending from the right wall to the left wall.

Observations were made in the upper part of the boiler using the special camera looking into the lower part of the screen tubes and using the particulate-counting camera looking into the front of the boiler, halfway up the screen tubes. The observed flow patterns were essentially the same as for the conventional air system.

While the novel air system had some positive features, it failed because the low-velocity primary air jets were ineffective at controlling the char bed (5). This problem, which undermined the success of the boiler retrofit, could not be anticipated from physical flow modeling. At Sandwell, we are now pursuing high-velocity primary jets, via boiler trials with two-wall primary air *(6)*. Subsequent physical flow modeling has confirmed the potential of partially interlaced air jets for improving gas flow patterns in recovery boilers *(7)*. At Sandwell, we are initiating other boiler trials with partially interlaced secondary air jets in other furnaces.

Conclusions

Physical flow modeling provides a good representation of the actual gross flow conditions in an operating recovery boiler. However, it cannot provide key information on the interaction of the gas flow with the liquor particles in flight and on the char bed. Therefore, while physical modeling can be used to investigate promising flow patterns, trials on operating recovery boilers remain the critical step in translating ideas into practical improvements.

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