Validation of CFD Models for Evaluating Hot-Air Recirculation in Air-Cooled Heat Exchangers

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Abstract

Air-cooled heat exchangers (ACHEs) are frequently used for process plants and power plants where steam or other process fluids must be cooled or condensed without a large local supply of cooling water. ACHEs, or "air coolers", work by moving ambient air across a series of finned tube bundles containing the fluid to be cooled, and then exhausting the heated air to the atmosphere. ACHEs are effective heat transfer devices, but because they use ambient air, their performance is influenced by air temperature, wind direction, and wind speed, and by the proximity of other air coolers and buildings. In particular, ACHEs can experience recirculation of hot exhaust air back to their air intakes, significantly reducing unit performance. Computational fluid dynamics (CFD) modeling provides an effective means to evaluate the cause of the recirculation problems and offer solutions to improve performance. CFD modeling was performed to evaluate recirculation problems at AGRIUM's Joffre Nitrogen Operation (JNO) plant in Joffre, Alberta, Canada. Two of the ACHE units at the JNO plant, a steam condensing unit and an ammonia condensing unit, were evaluated. During the summer months recirculation in the steam condenser ACHE limits the plant production by as much as 10%. CFD models were used to examine several different solutions to the recirculation problem, including adding windwalls around the exhaust bays and removing the center divider wall from the steam condenser ACHE. The modeling results indicated that adding wind walls would actually increase the recirculation for certain wind conditions, while removing the center divider wall would reduce recirculation for all wind conditions. Tests at the JNO plant were performed over a three-day period in September 1997 to validate the CFD models with velocity and temperature measurements from around the steam condenser. The CFD predictions were in excellent agreement with the measured data. Comparison of the measured and predicted air temperatures and velocity components around the steam condenser showed both qualitative and quantitative agreement.

Introduction

Background

Air-cooled heat exchangers (ACHEs) are frequently used for process plants and power plants where steam or other process fluids must be cooled or condensed without a large local supply of cooling water. ACHEs, or "air coolers", work by moving ambient air across a series of finned tube bundles containing the fluid to be cooled, and then exhausting the heated air to the atmosphere. ACHEs are effective heat transfer devices, but because they use ambient air, their performance is influenced by air temperature, wind direction, wind speed, and by the proximity of other air coolers and buildings. In particular, ACHEs can experience recirculation of hot exhaust air back to their air intakes, significantly reducing unit performance.

General rules for predicting the occurrence of hot-air recirculation in ACHEs have been around since the 1970's [1,2]. These studies were primarily based on experimental results from operating units and scale models. More recently, analytical work has been performed to predict the amount recirculation and its effect on unit performance for simplified ACHE geometries during windless conditions [3-5]. While these methods are helpful in determining the propensity for recirculation and its effect on the ACHE performance, they lack the complexity necessary to analyze many ACHE recirculation problems.

Computational fluid dynamics (CFD) provides an effective means to evaluate hot air recirculation problems and offer solutions to improve performance. CFD models, if done correctly, can account for the complex interactions between the ambient conditions (wind speed and air temperature), plant equipment and heated plumes that are often the cause of recirculation problems. CFD models have been used to evaluate various ACHE and plant configuration changes to improve overall performance [6]. The models provided sufficiently accurate predictions over a range of operating conditions which were not possible using other methods. With recent advances in computational speed and modeling capabilities, the complex three-dimensional geometries of the plant and ACHEs can now be modeled with only minor simplifications.

CFD modeling was performed to evaluate recirculation problems at AGRIUM's Joffre Nitrogen Operation (JNO) plant in Joffre, Alberta, Canada. The JNO plant uses waste heat created during the production of the anhydrous ammonia to generate steam and drive a synthesis gas compressor. The steam exiting the compressor is condensed by a forced-draft ACHE. The layout of the steam condenser ACHE at the plant results in significant hot air recirculation for the prevailing summer winds. The hot air recirculation can increase individual fan inlet temperatures as much as much as 17 °C (30 °F) and reduce the plant production by as much as 10%.

Objective

The objective of this work was to evaluate the recirculation problems for various wind conditions; provide solutions to reduce the recirculation during summer operating conditions and; validate the CFD model with field data from the JNO steam condenser. CFD predictions were made for various wind conditions and ACHE arrangements, including the addition of wind walls to the ACHE exhaust bays and removal of center dividing wall on the steam condenser ACHE. CFD predictions were also compared to velocity and temperature measurements made around the steam condenser ACHE in order to validate the model.

Plant Description

The Joffre Nitrogen Operation (JNO) Plant is located in Joffre, Alberta. The JNO plant layout is shown in Figure 1. There are two ACHE units at the plant, the steam condenser (E-404) and the ammonia condenser (E-509). Both units are oriented with their major axis along the north/south line. The steam condenser is 43.5 m (143 feet) long, 21.3 m (70 feet) wide and 9.8 m (32 feet) high and the ammonia condenser is 42 m (138 feet) long, 12.5 m (41 feet) wide and 6.7 m (22 feet) high. The steam condenser, shown in detail in Figure 2, is comprised of 18 Hudson Products variable-pitch fans. There are two fans per bay and the bays are oriented along the north/south axis of the plant. The fans operate in forced draft mode at a constant speed with a variable pitch to control the airflow. The fan intakes are located approximately 4.3m (14 feet) from the ground. The air is drawn into the bottom of the fan and flows through a bank of finned condenser tubes and out a louvered top. The sides of the steam condenser are also louvered to control the amount of outside air drawn into the fans. During winter operations much of the exhaust air is deliberately recirculated back to the fan inlets to keep the condenser tubes from freezing. The south end of the steam condenser has "garage" doors that allow heavy equipment access to fans. The south end doors remain open during summer operation of the plant, while the north end is completely closed off. There is also a center divider wall that separates the east and west-side fans in each bay. The design heat transfer load for this unit is 36.6 MW.

The ammonia condenser, shown in Figure 3, is comprised of 20 Hudson Products variable-pitch fans in the same basic layout as the steam condenser. The fan intakes for this unit are approximately 4.6 m (15 feet) from the ground. There is no danger of the ammonia condenser freezing, so this unit is completely open to flow on all sides. However, a center divider (or splitter) wall was recently installed below the fan intakes to reduce noise levels from the plant. The design heat transfer load for this unit is 21.7 MW.

There are several other buildings of note on the premises. The compressor building is located directly north of the steam condenser and the service building is west of the

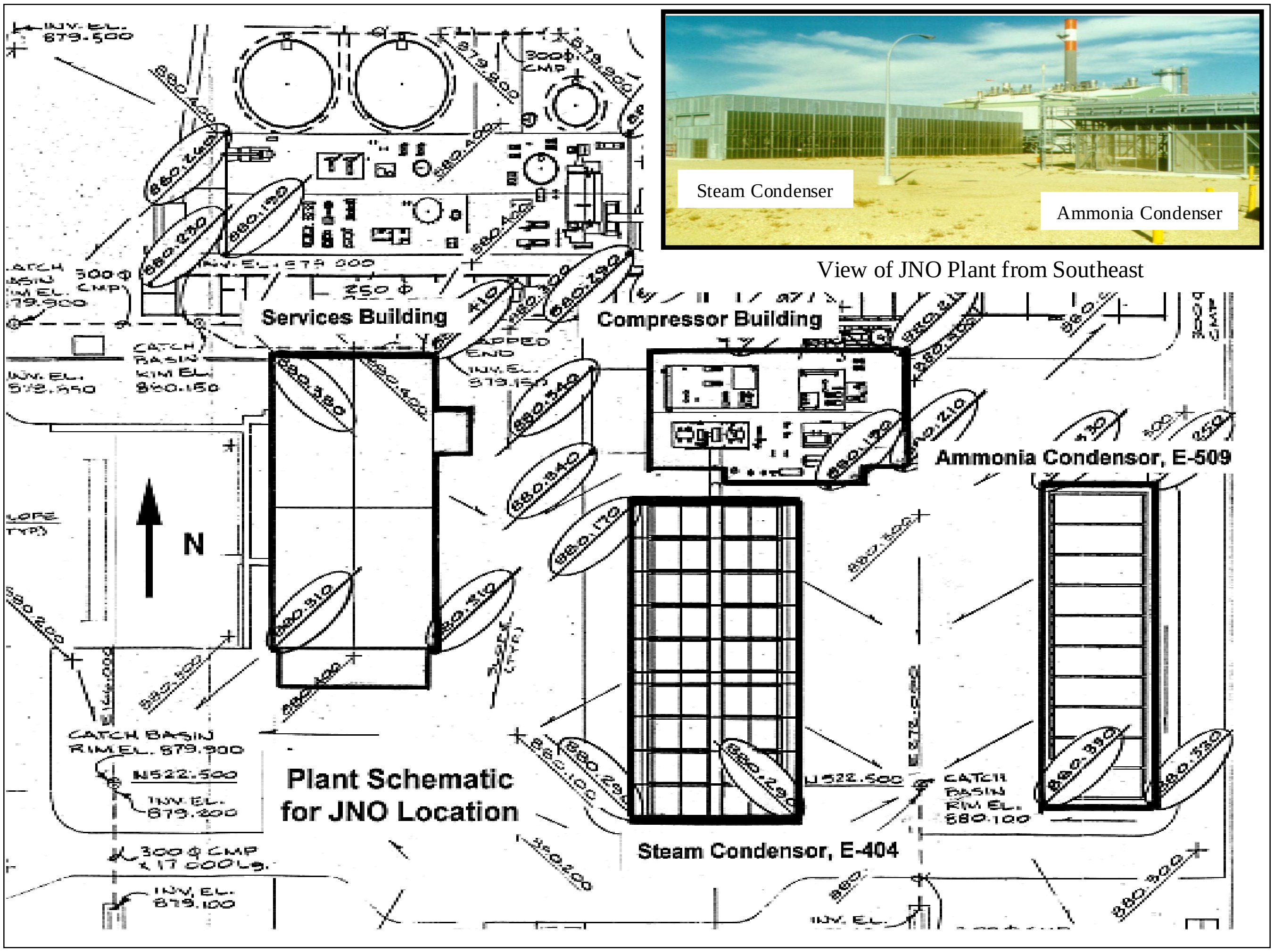


Fig. 1 Joffre Nitrogen Operation plant layout.

steam condenser. There are several other buildings shown in the layout, but preliminary modeling results indicated they do not affect the flow around the steam and ammonia condensers for the wind directions examined in this work and thus were not included in the model.

Technical Approach

Modeling Approach

McDermott Technology Incorporated's combustion model COMO, a multi-dimensional flow, combustion and heat transfer code, was used to perform numerical modeling of the JNO plant. COMO has been developed for fluid flow, heat transfer, and fossil combustion and pollutant reactions. The code is based on the time-averaged Navier-Stokes equations and incorporate turbulence using either standard k-ε or multiple-time-scale k-e models. Recent efforts have focused on unstructured discretizations using a cell-vertex form of the finite volume method [7]. Mass and momentum equations are solved on a collocated grid using a projection method; pressure-velocity coupling is achieved using Rhie and Chow [8] interpolation. Advection terms are treated using a bounded, high resolution (second order and higher) scheme to insure bounded, non-oscillatory solutions in regions of high gradients. An algebraic multigrid algorithm [9] is applied to solve the discrete equations. The model is applicable to structured, block-structured, or completely unstructured discretizations in either two or three dimensions.

Model Geometry. The JNO plant model geometries are shown in Figure 4. Shown are the nominal plant layout, the modified layout with 3.66 m (12 foot) high wind walls added to the exhaust bays of both the steam and ammonia condenser ACHEs and the validation test layout with the south end "garage" doors open to flow. There was also a model layout identical to the nominal

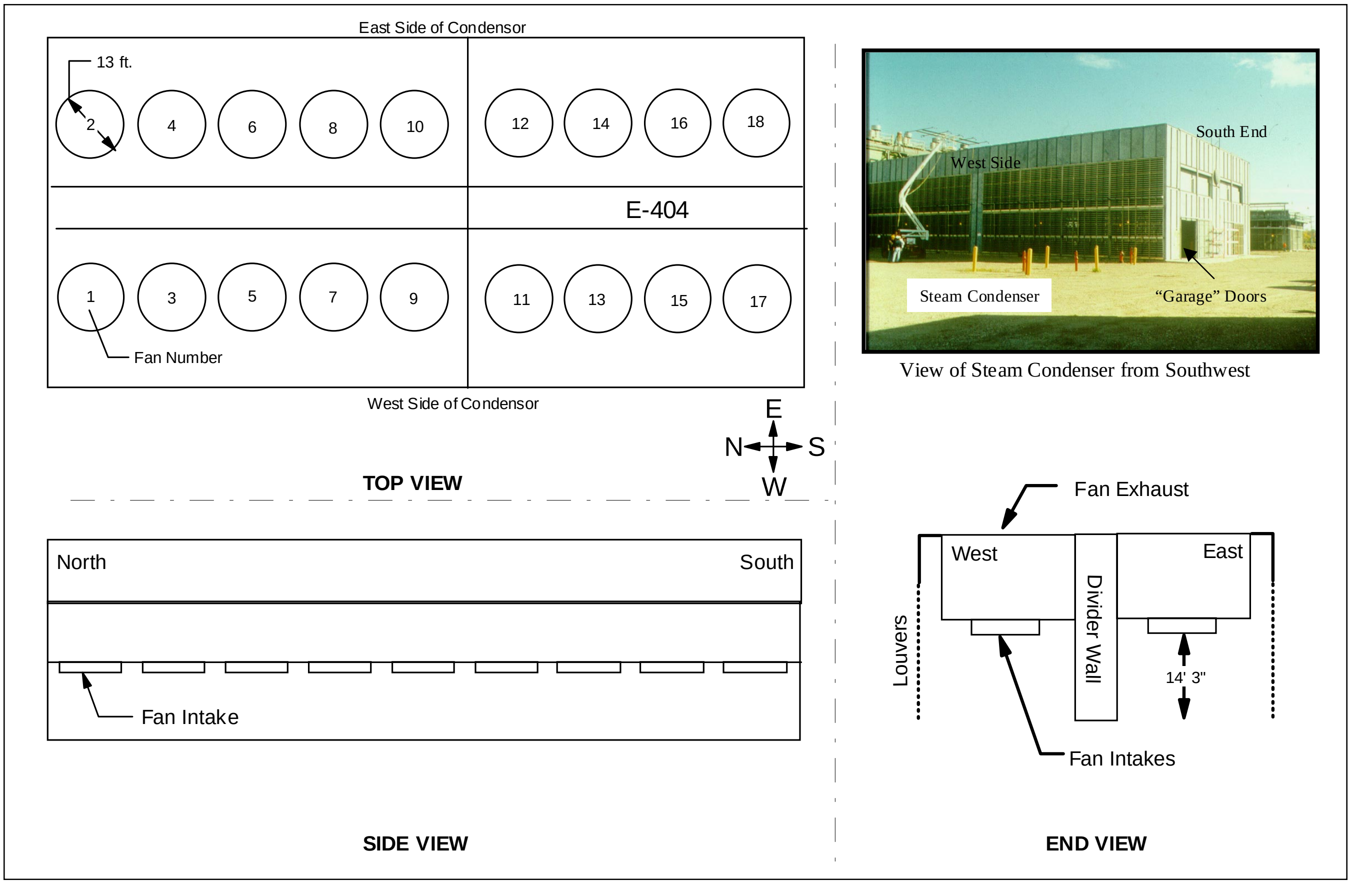


Fig. 2 Schematic of the steam condenser ACHE.

layout except that the center diving wall on the steam condenser ACHE was removed. The model layouts included the steam condenser ACHE, the ammonia condenser ACHE, the compressor building and the services building.

The computational domain is 500 m (1640 ft) wide, 750 m (2460 ft) long and 500 m (1640 ft) high. The domain size was chosen so that the boundary conditions would not affect the flow field near the buildings. The model was meshed with approximately 140,000 tetrahedral elements. Tetrahedral elements were used to generate the mesh because they simplified the model construction and allowed the resolution of small-scale equipment while still maintaining an economical number of control volumes. Comparison of the predicted flow patterns and temperature profiles between models using hexahedral elements and tetrahedral elements showed no appreciable differences.

Model Boundary Conditions. The boundary conditions for the model came from the measured ambient conditions and Hudson Products ACHE specification sheets. The measured wind speed and direction were averaged for the duration of a test. Two of the four sides of the domain, based on the wind direction, were specified as inlets and the other two sides were specified as outlets. The wind speed, direction and temperature for the two inlet domains were applied as a uniform velocity and temperature boundary condition at the model inlets. The bottom of the model (the ground) was specified as a wall boundary and the top was specified as a symmetry boundary condition. The symmetry boundary condition assumes no outflow out of the top of the domain. While this is not strictly true for this application, it is a fair representation as long as the heated plume is dissipated before it reaches the top of the model. The fan intakes were specified as mass sinks. The mass flow rate into the fans was taken from the ACHE specification sheets provided by Hudson Products. The ACHE fan exhausts were specified as velocity inlets. The mass flow rate and temperature at the fan exhaust were determined from the fan specification sheets and the design heat loads for the ACHEs.

Validation Testing

Data Acquisition and Instrumentation. The data acquisition system consisted of an instrumentation grid, an ambient wind condition station, 4 fan thermocouples, a man-lift, a data acquisition unit and wiring to link the instrumentation to the data acquisition unit. The instrumentation grid had 10 anemometers and 10 thermocouples attached to a steel structure. The steel structure was mounted on a man lift so it could be elevated to the top of the steam condenser. An anemometer and thermocouple were also placed approximately 50 feet from the southeast corner of the steam condenser to measure the ambient wind speed, direction and temperature. In addition, thermocouples were placed at the inlets to fans 8, 9, 11 and 12 (see Figure 2). The thermocouple and anemometer readings were routed to a central data acquisition unit. A FLUKE 2286 A data logger was used to read the raw voltages from the thermocouples, wind vanes and anemometers and do the calculations to transform the data to engineering units.

Temperature and velocity measurements were made on both the east and west sides of the steam condenser near the top (~9.8 m [32.5 ft.] from the ground). The measurement locations were chosen in an effort to capture the strength and location of the recirculation zones around the steam condenser for the prevailing summer wind conditions. Regions of down flow with temperatures higher than ambient indicate recirculation from the steam or ammonia condenser exhaust. The instrumentation grid, shown in Figure 5, was approximately 3 m (10 feet) wide and 6 m (20 feet) long and was used to measure the temperature and velocity at 10 points simultaneously. Temperature and velocity measurements were made at each grid point. The temperature measurements were made with type K thermocouples. The velocity measurements were made with a cup anemometer attached to a wind vane. The cup anemometer was used to measure the wind speed and the wind vane was used to measure the direction. Due to the limitations of the wind vane, only two components of the wind direction could be measured. Based on the desired

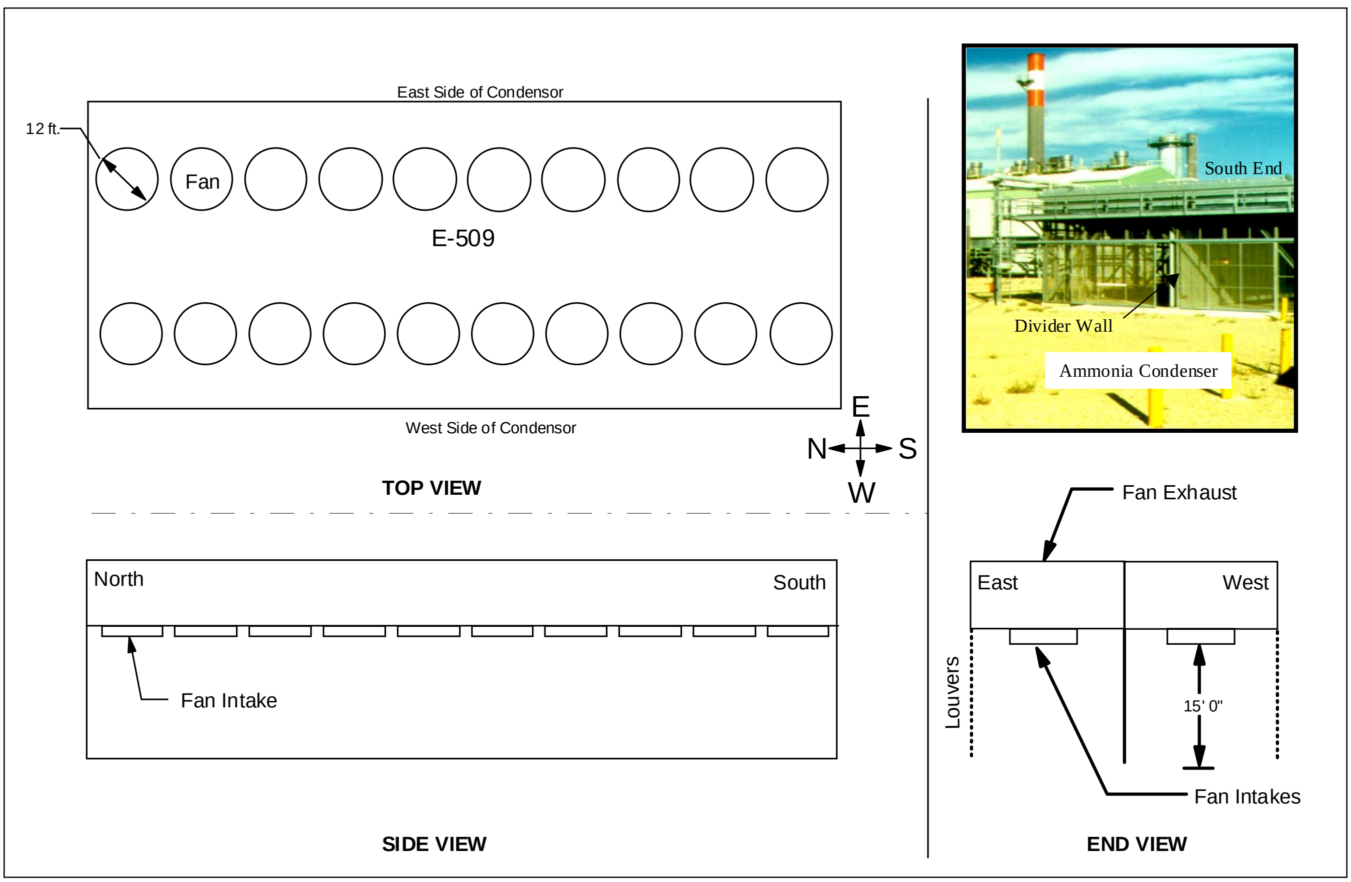


Fig. 3 Schematic of the ammonia condenser ACHE.

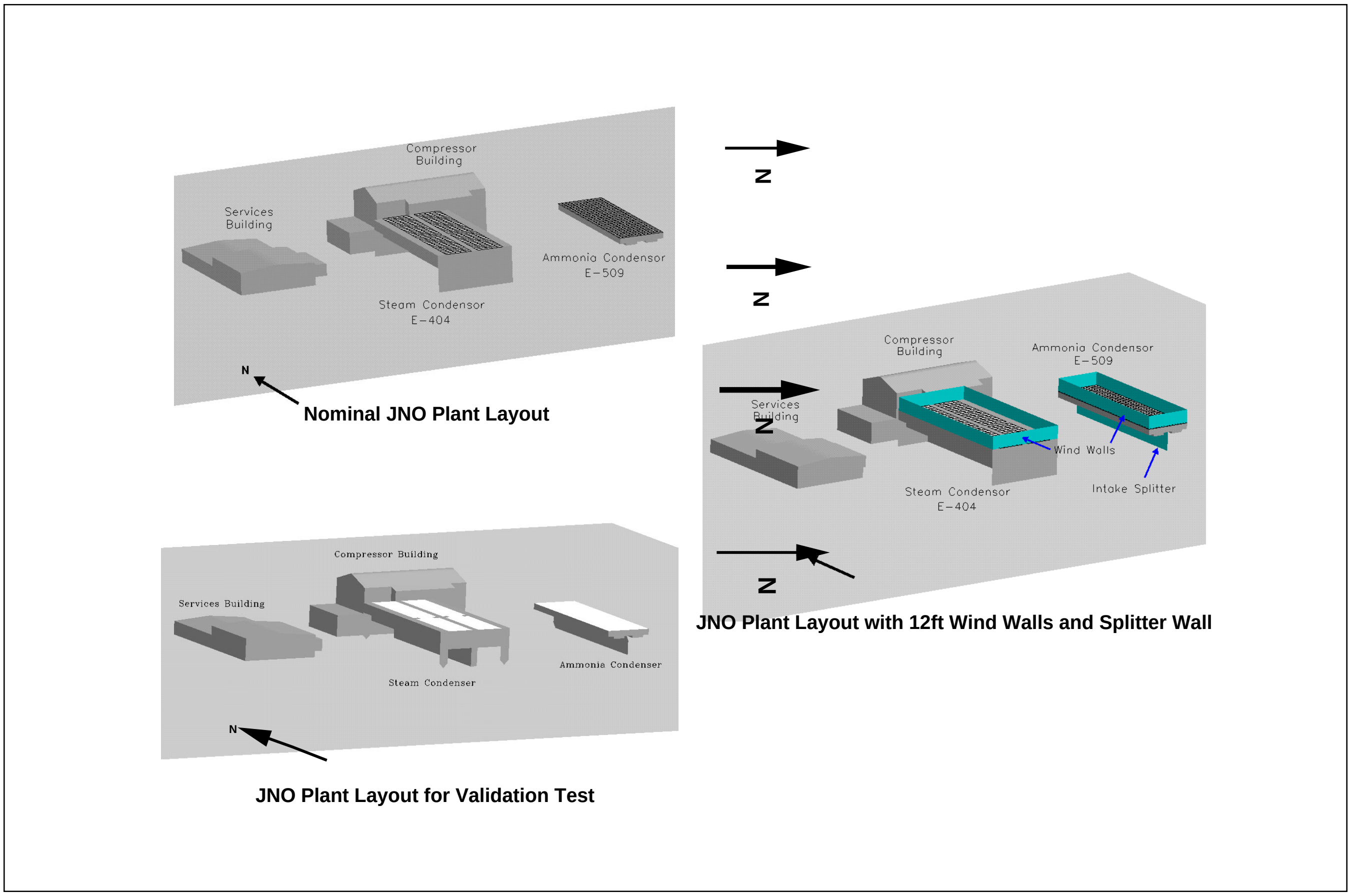


Fig. 4 CFD model layouts.

information, the wind vanes were oriented so that they could measure the vertical component and the east/west component of the velocity. The grid was positioned at various locations around the steam condenser. Data was taken on both the east and west sides of the unit and the grid locations are shown in Figure 6. The side of the steam condenser (east or west) and a letter indicating its relative position, as shown in Figure 6, denoted the grid location. The grid locations were laid out to acquire data every 1.5 m (5 ft) along the length of the unit. Three additional locations were used on the west side of the condenser (locations O, P, and Q in Figure 6) to help capture the recirculation zone during southeastern winds. The data acquisition procedure was to position the grid at a given location, acquire data for five minutes then reposition the grid to the next location. This procedure was continued until all the grid locations were sampled, or the wind stopped or shifted, which ever came first.

Ambient wind speed and direction fan inlet temperatures and steam condensation rates were recorded from the control room monitors for each grid location measurement. The ambient wind speed, direction and temperature were also recorded by the data acquisition unit at the local station set up at the southeast corner of the steam condenser. Wind speed and direction were also monitored from a dedicated weather station roughly ½ mile north and ½ mile west of the plant. The weather station data was taken every 5 minutes and reported as hourly averages. The three sources of ambient wind speed and directions were compared at regular intervals. Typically all three measurements agreed to within the uncertainty of the measurement equipment, but on the occasion that one of the methods did not agree with the other two, the odd measurement was removed from the data set. The air temperature at each fan intake was recorded in the control room for each grid position. The fan intake temperatures at fans 7, 8, 11 and12 were also recorded by the data acquisition system for each grid position. Those data were averaged over the duration of the test to get average fan intake temperatures.

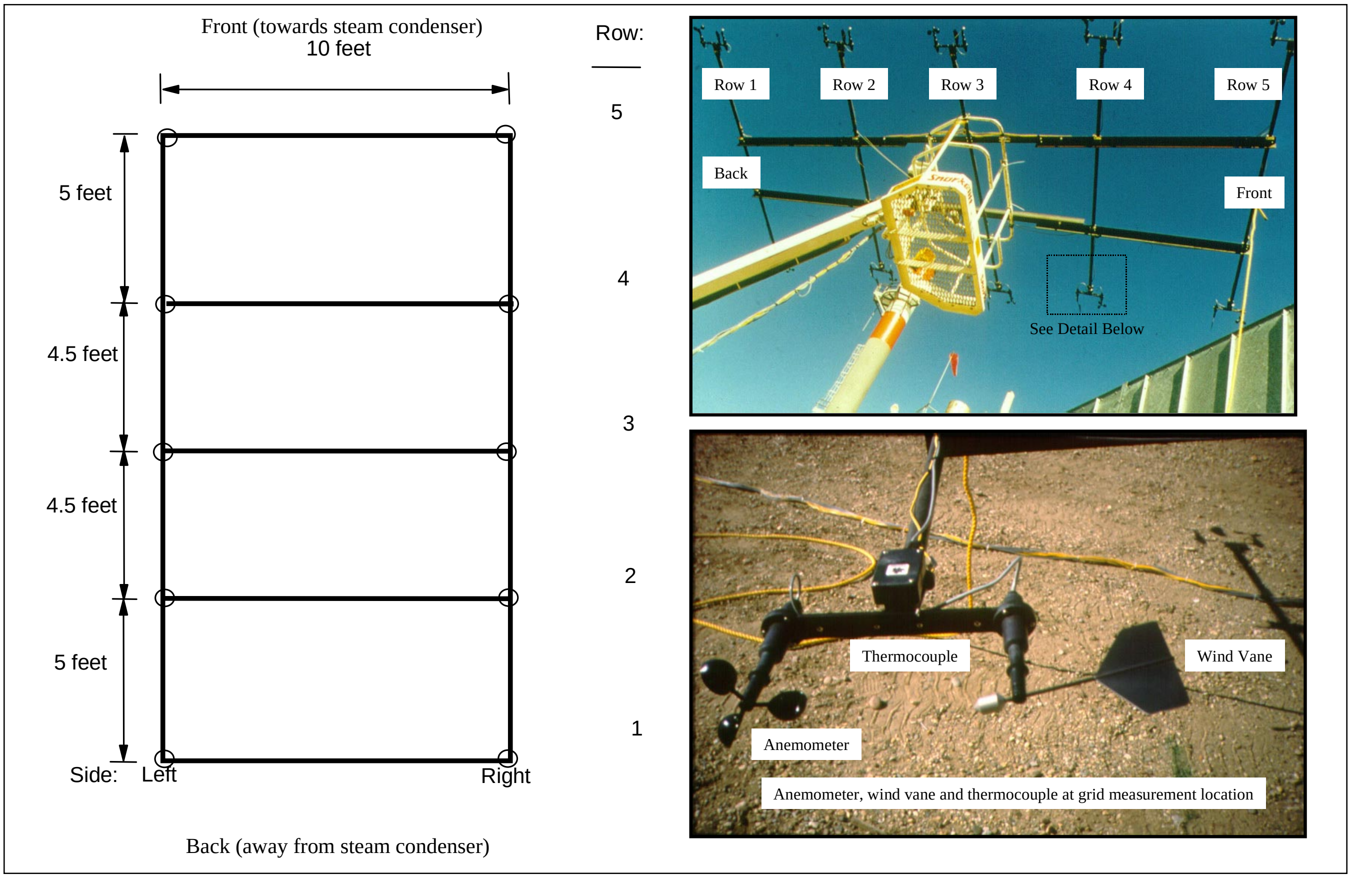


Fig. 5 Instrumentation grid used for data acquisition.

Test Conditions. Data was taken over a three-day period from September 24^{th}, 1998 to September 26^{th}, 1997. Conditions where the wind was out of the southeast were of primary interest, since they represent the prevailing summer winds. During all tests, the fans were run at maximum flow, both sets of louvers were wide open and the south end doors were open. This is typical of summer operation and represents the ACHE design specifications and heat load for this unit. The test was performed with a moderate southeast wind, 12.6 km/hr (~8 miles/hr), and the divider wall between the east and west fan bays intact.

Results

Parametric Modeling Results

The operating conditions for five of the cases examined with the CFD model are summarized in Table 1. Ambient air at 30 ^{o}C (85 ^{o}F)with winds from the south-southeast (SSE) and east-southeast (ESE) at 15 km/hr (9.3 mph), respectively, were evaluated for both the nominal plant

Table 1 Summary of modeled plant configuration and wind conditions.

Case	Nominal Layout	Wind Walls	Steam Condenser Center Dividing Wall	Wind Direction	Wind Speed	Air Temp.
1	y	n	y	SSE	15 km/hr (9.3 mph)	30 ^{o}C (85 ^{o}F)
2	y	n	y	ESE	15 km hr (9.3 mph)	30 ^{o}C (85 ^{o}F)
3	n	y	y	SSE	15 km/hr (9.3 mph)	30 ^{o}C (85 ^{o}F)
4	n	y	y	ESE	15 km/hr (9.3 mph)	30 ^{o}C (85 ^{o}F)
5	n	n	n	SSE	15 km/hr (9.3 mph)	30 ^{o}C (85 ^{o}F)

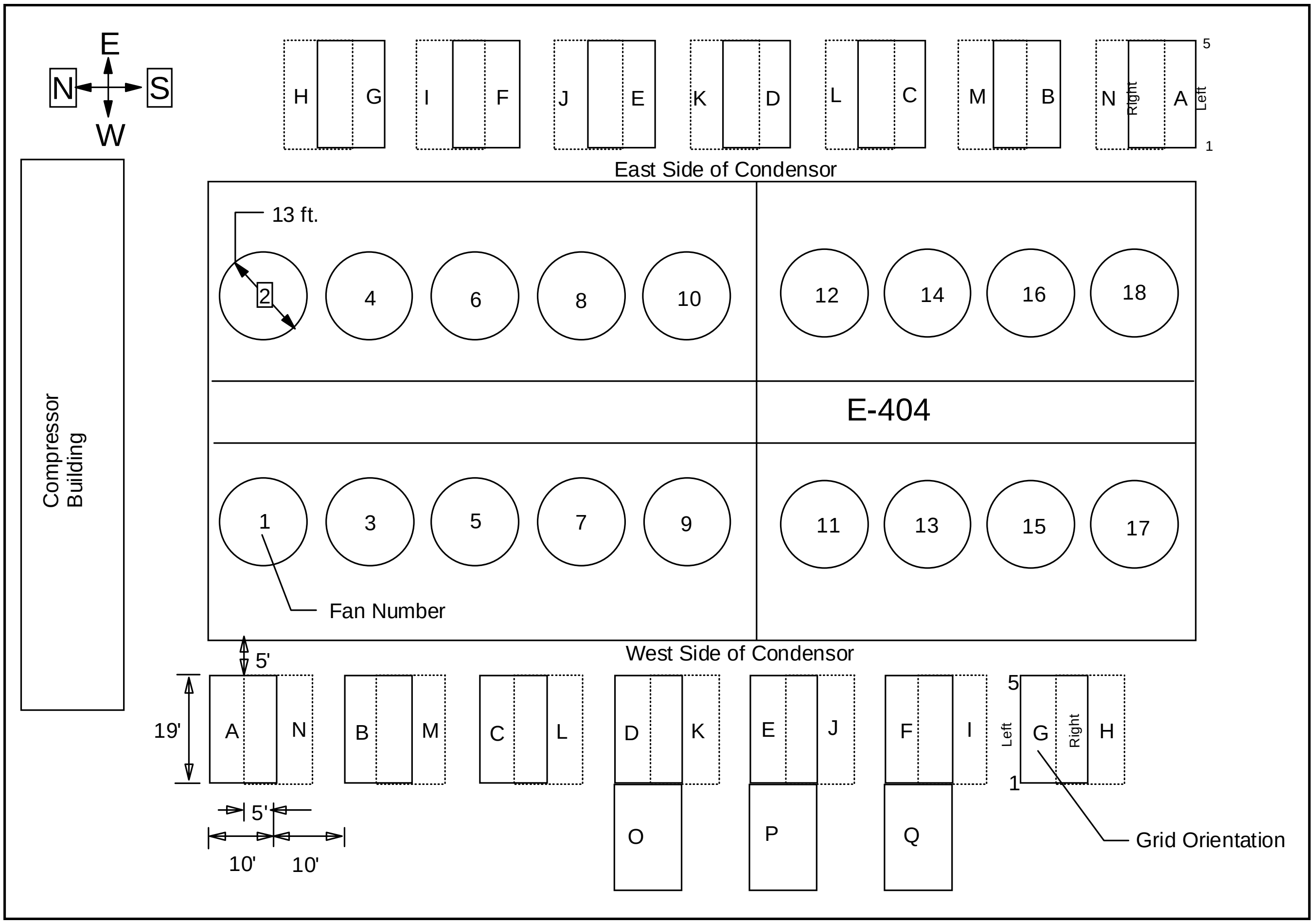


Fig. 6 Measurement locations around the steam condenser for validation test.

layout and the modified layout (wind walls). Only the SSE wind conditions were evaluated for the layout with no center dividing wall on steam condenser ACHE.

Some typical results are shown in Figures 7 through 9 for the nominal layout with SSE winds. Plots of the flow patterns around the ACHE are illustrated using flow traces colored by the local air temperature. Flow traces, used here to visualize flow direction, are equivalent to smoke traces that follow the local flow velocity of the air. Note that in the plan view from below in Figure 7, the fan intake regions are also colored by the local air temperature. With the wind from this direction (SSE), air to the ACHEs is not obstructed by any upwind buildings. The ammonia condenser is open on all sides and allows the fans to draw air from the south, east and west sides of the unit. The center dividing wall and front (south) end of the steam condenser ACHE block air from entering the west side fan inlets easily and creates a low pressure region on the west side of the unit. This low pressure region creates a hot air recirculation zone on the west side of the steam condenser ACHE. The hot air recirculation is illustrated nicely by the flow traces in Figures 7 and 8. The pressure contours at ground level and the air temperature contours at an east-west cut through the ACHEs are shown in Figure 9. The low pressure region on the south west corner of the steam condenser is clearly evident as is the effect of the wind on the hot air plumes emanating from both ACHEs.

The results from the five modeling cases are summarized in Table 2. Cases 1 and 2 show the effect of wind direction on the hot air recirculation. The recirculation is indicated by the average temperature difference from the ambient at the fan intake locations of the ACHEs. In general the steam condenser ACHE experiences much more hot air recirculation than the ammonia condenser ACHE. The Case 2 results show more recirculation for the steam condenser ACHE and slightly less recirculation for the ammonia condenser ACHE than the Case 1

Table 2 Comparison of predicted intake air temperatures differences (from ambient) for the ACHEs.

Case	Description	Wind Conditions	Steam Condenser West-Side Average	Steam Condenser East Side Average	Ammonia Condenser West Side Average	Ammonia Condenser East Side Average.
1	Nominal Layout	SSE 15 km/hr, 30 ^{o}C	5.1 ^{o}C	0.1 ^{o}C	0.8 ^{o}C	1.4 ^{o}C
2	Nominal Layout	ESE 15 km/hr, 30 ^{o}C	3.4 ^{o}C	0.1 ^{o}C	0.6 ^{o}C	0.8 ^{o}C
3	Wind Walls	SSE 15 km/hr, 30 ^{o}C	6.3 ^{o}C	0.6 ^{o}C	0.2 ^{o}C	0.8 ^{o}C
4	Wind Walls	ESE 15 km/hr, 30 ^{o}C	7.8 ^{o}C	0.3 ^{o}C	0.1 ^{o}C	0.5 ^{o}C
5	Steam Condenser Divider Wall Removed	SSE 15 km/hr, 30 ^{o}C	3.5 ^{o}C	0.1 ^{o}C	0.8 ^{o}C	1.4 ^{o}C

results. Adding the wind walls (Cases 3 and 4) decreases the recirculation at ammonia condenser ACHE for both wind directions. However, it actually increases the hot air recirculation at the steam condenser ACHE. The ammonia condenser wind walls provide added obstruction to air flow to the steam condenser ACHE, increasing its hot air recirculation. Removing the center dividing wall from the steam condenser ACHE significantly reduces the hot-air recirculation for the SSE wind direction, but does not affect the ammonia condenser. Removal of the center divider wall should reduce hot-air recirculation for all wind directions, but most dramatically for east-west cross winds.

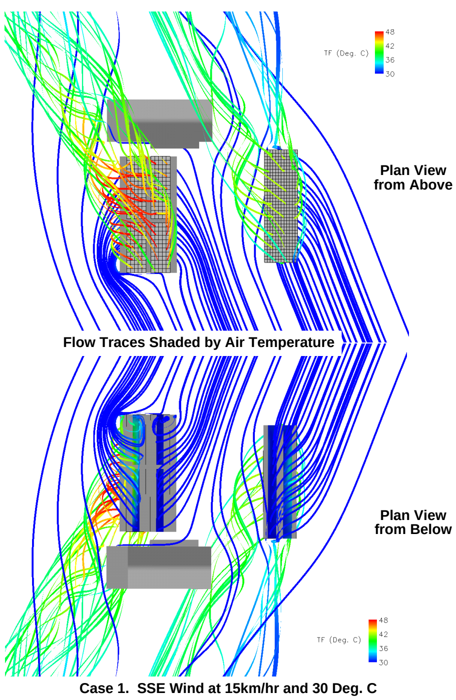


Fig. 7 Plan views of flow patterns around the ACHEs for typical summer wind conditions.

Validation Test Modeling Results

The operating conditions for the validation modeling case is summarized in Table 3. The operating conditions were compiled from the measured data, control room data, weather station data and the ACHE specification sheets. A complete set of data took approximately 5 to 6 hours to acquire. Gusting and shifting winds were evident at times, which is a limitation of the validation data. The test

Table 3 Ambient conditions for modeling of ACHE validation tests.

Parameter	Value
Wind Speed	12.6 km/hr (7.84 mph)
Wind Direction 0^{o} = North 90^{o} = East	127^{o}
Ambient Temperature	23.8 ^{o}C (74.3 ^{o}F)
Steam Condenser Exhaust Temperature	41.0 ^{o}C (105.2 ^{o}F)
Ammonia Condenser Exhaust Temperature	36.1 ^{o}C (96.4 ^{o}F)

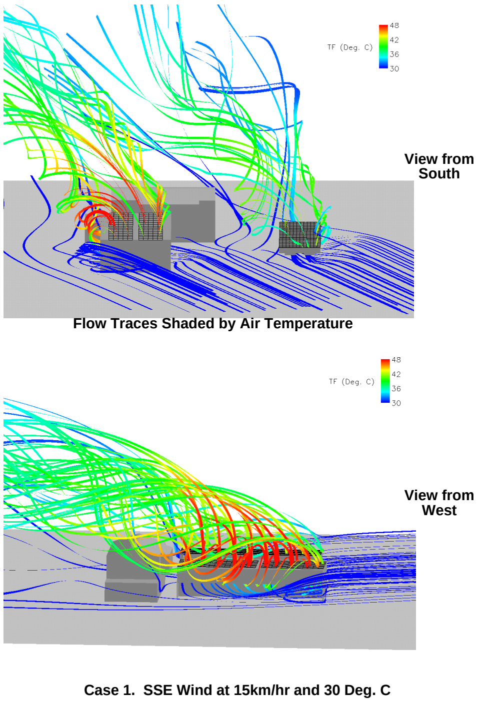


Fig. 8 Isometric views of flow patterns around the ACHEs for typical summer wind conditions.

was terminated if the wind direction changed by more than +/- 90 degrees from the starting wind direction. Three sources of ambient conditions were monitored and the data was compared at set times. Typically the three agreed to within the uncertainty of the measurements. If all three agreed, the weather station data was used for the far field ambient inlet boundary condition in the model because it was thought to the better of the three measurements. If one of the measurements didn't agree, the odd measurement was disregarded and the other two were averaged for the duration of the test and the average was used.

Comparisons of CFD Results to Data

For the validation test, the winds were from the southeast (127 ^{o}, where 0^{o} = north 90^{o} = east) at 12.6 km/hr (7.84 mph). For SE winds, a low-pressure zone is created on the downwind (west) side of the steam and ammonia condensers. This low-pressure region forces hot air from the exhaust to be drawn back down into the west side fan intakes.

The predicted and measured air temperatures near the top of the steam condenser are compared in Figure 10 and the agreement is excellent. Slightly different scales were used for the predicted and measured contours to account for the changing ambient temperatures during the day (4.5 ^{o}C [8 ^{o}F]) and non-uniform fan outlet temperatures. The range of predicted temperatures went from 24 ^{o}C to 41 ^{o}C (74 ^{o}F to 105 ^{o}F), while the range of measured temperatures went from approximately 21 ^{o}C to 46 ^{o}C (70 ^{o}F to 115 ^{o}F). The predicted location of the hot air on the west side of the steam condenser is nearly identical to that measured. The predictions for east side show slightly warmer temperatures near the north end, which is also shown in the predictions. This warm air comes from the ammonia condenser exhaust. The measured data also shows some warm air regions near the middle of the steam condenser that was not predicted. This warm air in the center region is also coming from the ammonia condenser exhaust and is due to the winds shifting slightly more from east during the data collection of this region.

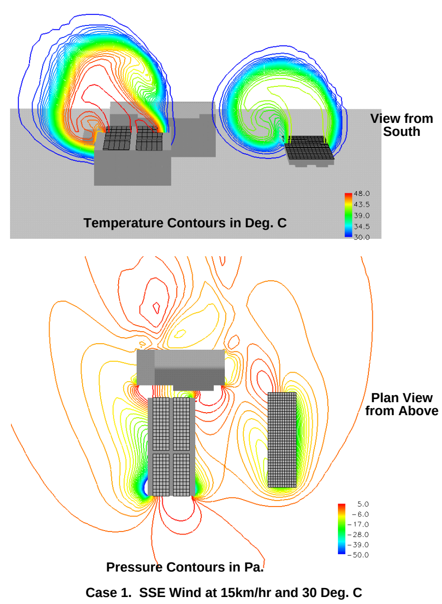
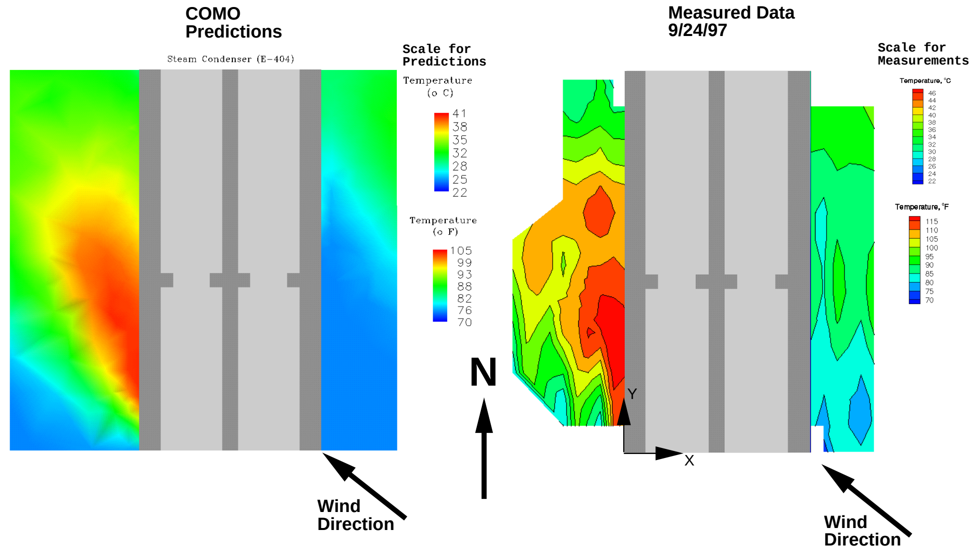


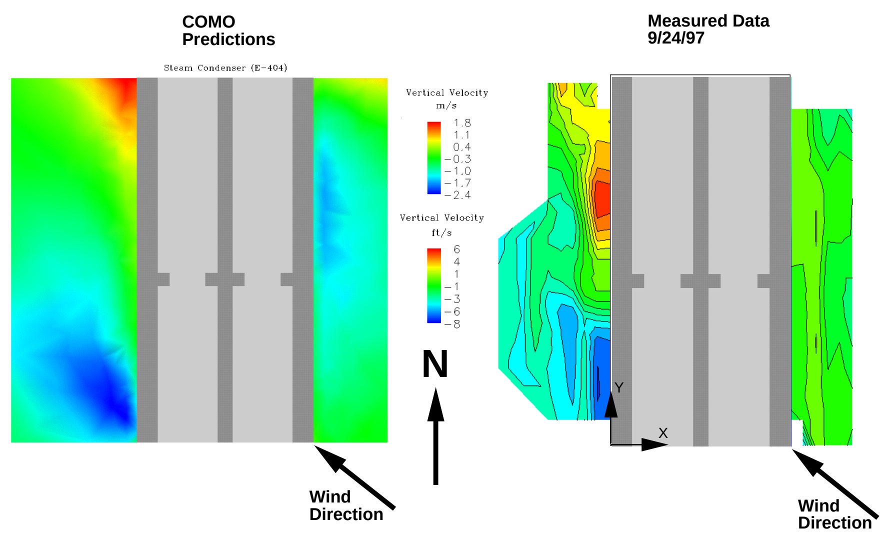
Fig. 9 Temperature and static pressure contours around the ACHEs for typical summer wind conditions.



Air Temperature Contours Near Top of Steam Condenser

SE Wind (127 °) at 12.6 km/hr (7.8 mph) and 24 °C (74 °F)

Fig. 10 Temperature and static pressure contours around the ACHEs for typical summer wind conditions.



Vertical Velocity Contours Near Top of Steam Condenser

SE Wind (127 °) at 12.6 km/hr (7.8 mph) and 24°C (74 °F)

Fig. 11 Predicted and measured vertical velocities near the top of steam condenser for validation test.

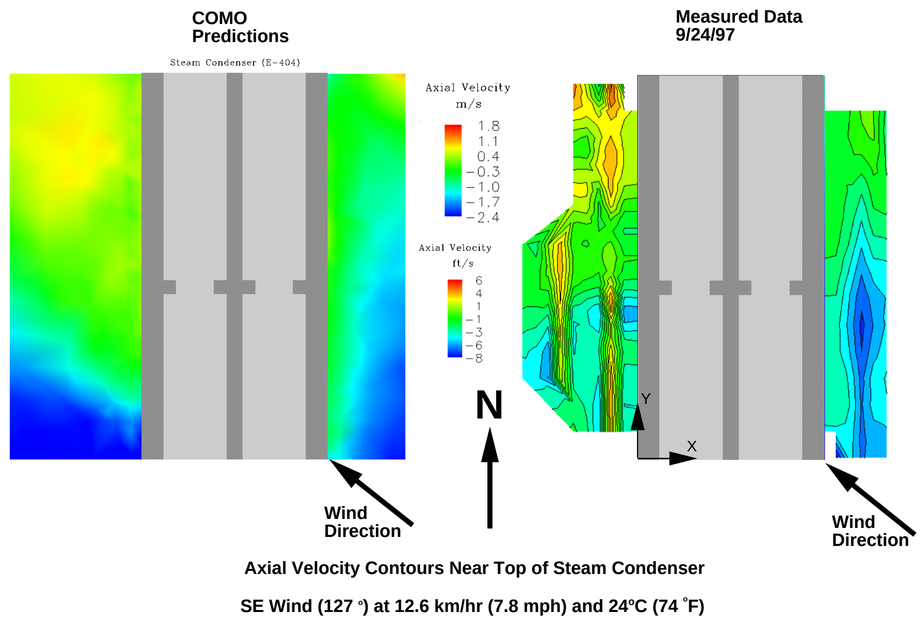


Fig. 12 Predicted and measured east/west velocities near the top of steam condenser for validation test.

The predicted and measured vertical velocities are compared in Figure 11. Once again the agreement is very good. On the west side of the steam generator the predicted region of down flow (negative vertical velocities) from the south end to the middle is confirmed by the measurements as is the strong up-flow region near the north end of the condenser. The comparisons are not quite as good for the east side of the condenser. Down flow is predicted to occur in the middle region, but areas of up-flow and quiescent flow were measured.

The predicted and measured axial (east-west) velocities are compared in Figure 12. Good agreement is also seen for the axial velocity comparisons. The predicted axial velocities on the west side of the steam condenser show strong east velocities (negative axial velocities) near the south end, and moderate west velocities (positive axial velocities) near the north end. The measured axial velocities show the same trends, but the west velocities are a little stronger near the north end and small regions of localized western velocities exist near the south end. The comparisons on the eastern side of the steam condenser are a little better. Both the predicted and measured axial velocities show east velocities for nearly the entire region, except the extreme north end where a small region of west velocity is seen.

The comparisons between the predicted and measured conditions near the top steam condenser showed good agreement. However, the fan inlet temperatures determine the true measure of the hot air recirculation on the ACHE performance. The measured and predicted fan intake temperatures are compared in Figure 13. The predicted fan intake temperatures were calculated by integrating the predicted temperatures over the fan intake surface in FIELDVIEW, a commercial post-processing package. For most of the steam condenser fans, the agreement between the predicted and measured fan intake temperatures are within 2 °C (4 °F). The main exceptions are for fans 11 through 17 on the west side and south end of the steam condenser. The temperatures measured in the control room for those fans range from 4 °C to 11 °C (9 °F to 18 °F) higher than that predicted by COMO. The thermocouples recorded by the data acquisition unit confirm the higher temperatures for these fans.

Conclusions

The results presented in this paper illustrate how CFD models can be used to evaluate and reduce hot air recirculation problems in ACHEs. CFD models were used to evaluate hot air recirculation for two forced-draft ACHEs at AGRIUM's JNO plant in Joffre, Alberta. The model was able to predict flow patterns for the existing plant geometry and screen the proposed modifications for reducing hot air recirculation. The CFD model showed that hot air recirculation is much more prevalent in the steam condenser ACHE than in the ammonia condenser ACHE during summer wind conditions, which was confirmed by plant personnel. In addition, the model results suggest that removal of the center dividing wall is more effective at reducing hot air recirculation than adding wind walls to the exhaust bay for the steam condenser ACHE. Additional confidence in the model predictions was gained via the successful validation testing performed at the plant. The comparison of the predicted air temperatures, air velocities and fan inlet temperatures to the measured values around the steam condenser ACHE showed excellent agreement, both qualitatively and quantitatively.

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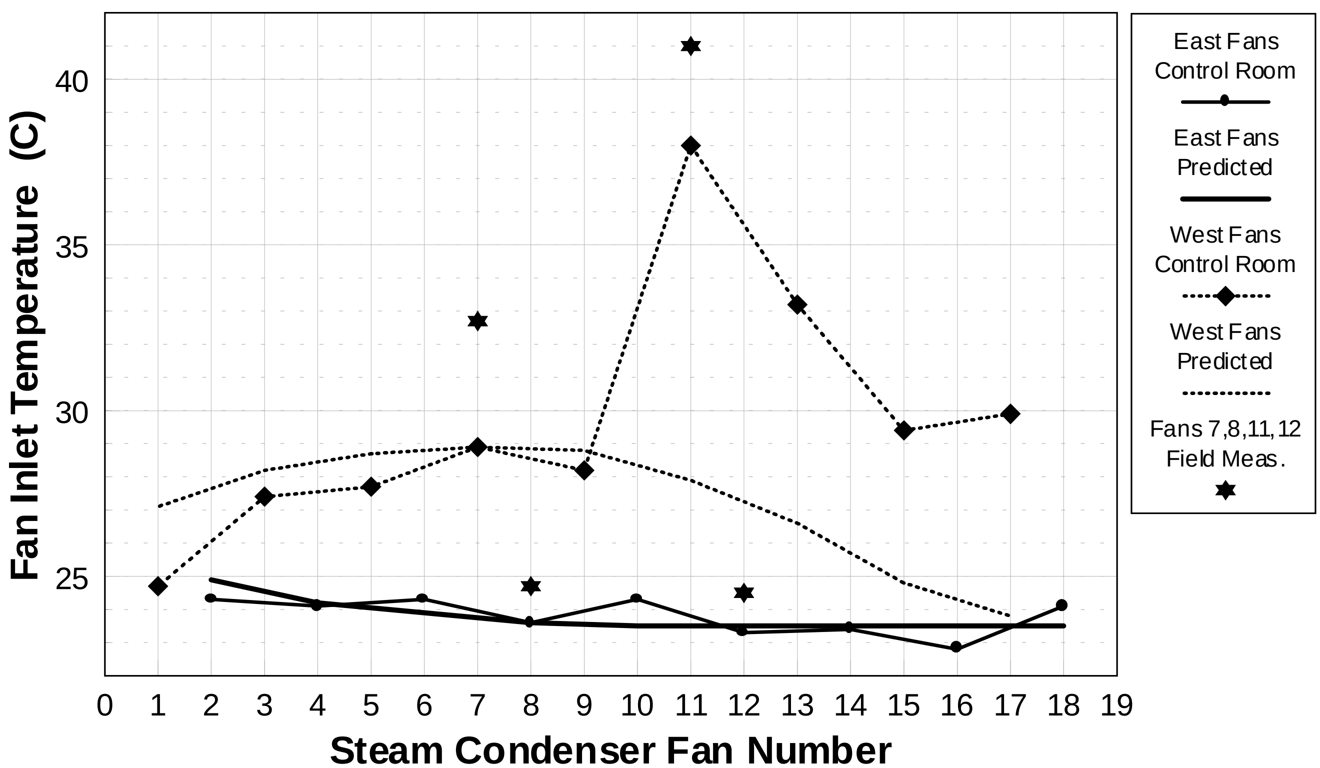

Fig. 13 CFD validation test results.

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