EXECUTIVE SUMMARY

FINAL REPORT ARTI-21CR/610-40040-01
INVESTIGATION OF BUILDING EXHAUST AIR RE-ENTRAINMENT INTO OUTDOOR AIR INTAKES OF PACKAGED OUTDOOR HVAC EQUIPMENT-PHASE I

Packaged HVAC equipment is often used to supply outdoor ventilation air along with its heating and cooling functions. In many cases, however, the outdoor air near the packaged HVAC equipment may be contaminated with stale air from an exhaust vent, or with flue gas vented by a furnace or boiler. When this equipment is operated in the economizer mode a significant percentage of the building exhaust air may be re-entrained into the fresh-air intake and the quality and quantity of exhaust air that is re-entrained can have a negative impact on the indoor air quality.

This report presents the results of the first phase of a multi-phase research program that is intended to develop an understanding of re-entrainment of flue gases and building-air exhaust in packaged HVAC equipment. The objectives of Phase I were to determine the design factors that affect the amount of air that is re-entrained in packaged HVAC equipment, and to identify the relationships that exist between the percentage of exhaust air re-entrained and separation distances, direction of airflow, and air velocities. The results are to be used to develop methods for estimating the percentage of flue gas and exhaust air that is re-entrained in a typical packaged product, and to recommend design guidelines that may be incorporated into industry standards for minimizing re-entrainment.

PLUME DISPERSION MODELS

Plume dispersion modeling is based primarily on the results of tests conducted in wind tunnels on scale models of buildings. The most recent work included vortex generators, barriers, and distributed surface roughness to simulate the flow field turbulence that exists in wind-driven flow fields. Dilution ratio measurements have been made on different surfaces of scale model buildings, for a wide variety of building geometries. The results have led to the development of analytical expressions to predict the dilution ratio of the plume based on distance, turbulence level, and the characteristics of the exhaust flow.

In the plume dispersion models included in Chapter 15 of the 1997 ASHRAE Fundamentals Handbook (also in Chapter 43 of the 1999 ASHRAE HVAC Applications Handbook) the dilution of exhaust gases is given as the sum of two parts: the initial dilution of the exhaust gases caused by turbulence in the exhaust jet, and the dilution caused by atmospheric turbulence. The first part accounts for the apparent initial dispersion of the plume that occurs due to internal turbulence at the exit of the exhaust. The second part accounts for the dilution caused by the action of atmospheric turbulence and increases with the square of the distance from the source, and is inversely related to exhaust velocity. On this project we tested these models for application to the much smaller flow fields around packaged HVAC equipment, on a scale of 10 feet (3 meters) or less.

For the large-scale flow field the atmospheric turbulence dilution factor that depends on distance is the dominant factor. At the smaller scale of packaged equipment, and the short distances between exhaust and intake, the exhaust turbulence factor becomes important. This would suggest that the re-entrainment of flue-gas exhaust and building air exhaust by the unit will depend as much on the design characteristics of the exhaust system as it does on the separation distance between the exhaust and the intake. Over the short distances from exhaust to intake, the influence of jet velocity, jet direction, wind direction, and unit geometry may overwhelm the influence of the distance parameter in many cases.

EXPERIMENTAL APPROACH

Tests were conducted on a 10-ton (35 kW cooling) packaged unit installed on the roof of a laboratory building. The unit contained a gas furnace with an input rate of 235,000 Btu/hr (69 kW). The re-entrainment of flue-gas with the furnace operating or building-air exhausted during economizer operation were measured over a wide range of conditions. The unit was instrumented to measure and record the CO_2 concentration in both the exhaust and fresh air intake of the unit. A weather station was placed on the roof that measured the wind speed, the wind direction, the ambient temperature, and the humidity. Thermocouples measured the temperature of the fresh-air intake and the flue-gas exhaust of the HVAC unit.

The re-entrainment of flue-gas exhaust from the gas furnace was measured over a 20-minute period each hour, 24 hours per day, seven days per week. The combustion-generated CO_2 was used as the tracer gas to determine the dilution of the flue-gas plume. The average concentrations of CO_2 in the exhaust and intake air streams were measured during a 10-minute burner on-time and used to determine the amount of entrainment of flue gases into the fresh-air intake.

When operating the unit in the economizer mode the exhaust-air stream was spiked with CO_2, and the tests were conducted primarily during working hours. In this case, the 20-minute data collection cycle was conducted two times per hour. In both cases, the fraction of exhaust gases in the fresh air intake was determined from the measured fresh-air intake and exhaust gas CO_2 concentrations.

FLUE-GAS EXHAUST ENTRAINMENT

Flue-gas entrainment data were obtained for three different flue-gas exhaust configurations. These included a tall vertical vent, a short vertical vent, and a downward facing vent. These three configurations encompass the typical vent configurations of the major manufacturers of packaged HVAC equipment. The tall vertical vent extended about 10 inches (25 cm) above the top of the unit. Tests were conducted at a firing rate of 235,000 Btu/hr (69 kW) with a flue-gas exhaust rate of about 110 CFM (52 l/sec) at 380 F (193 C). The exit flow velocity was about 30 ft/sec (9 m/sec).

The flue-gas entrainment data are presented as the dilution ratio, the inverse of the fraction of exhaust gas entrained. The minimum dilution ratio (i.e., the greatest amount of re-entrainment) measured for the tall vertical vent was 1284, corresponding to only 0.08 percent entrainment of flue gases in the fresh air intake. The minimum dilution ratio occurred at a wind direction between 150 and 155 degrees azimuth angle. This corresponds closely with the azimuth angle of a line drawn through the center of the flue-gas exhaust vent and the center of the fresh-air intake hood, which measured 152 degrees azimuth angle. The minimum dilution ratio was found to be virtually independent of wind speed, and occurred at large values of wind turbulence.

The short vertical vent outlet was 30 inches (75 cm) above the roof, and 28 inches (71 cm) below the top of the unit. The minimum dilution ratio measured was 368, a factor of 3.5 lower than for the tall vertical vent. As with the tall vertical vent, the minimum dilution ratio occurred at a wind direction of about 152 degrees azimuth angle. For the short vertical vent the flue-gas entrainment depends on wind speed; the minimum dilution ratio occurred at high wind speeds. Unlike the tall vertical vent, the minimum dilution ratio for the short vent occurred at relatively low wind turbulence.

A downward facing flue-gas vent is sometimes used on packaged HVAC equipment. The downward facing vent tested had its vent outlet directed downward about 20 inches (50 cm) above the roof surface. The minimum dilution ratio measured was 290, about 30 percent lower than the measurement for the short vertical vent. These data suggest that the minimum dilution ratio for this vent occurs over a broader range of wind directions than for the vertical vents, ranging from 152 to 190 degrees azimuth angle. The minimum dilution ratio occurred at wind speeds less than 1 ft/sec (0.3 m/sec), and at very low values of wind turbulence.

BUILDING-AIR EXHAUST RE-ENTRAINMENT

A series of tests were conducted to measure the re-entrainment of building-air exhaust with the packaged HVAC unit operating in the economizer mode. In the economizer mode the unit discharges part or all of the return air from the building and draws in a like amount of fresh make-up air. The economizer assembly for the test unit consisted of an axial fan to discharge the return air, a gravity louver at the fan outlet to prevent back-flow when the fan is off, and an exhaust hood. The building-air exhaust is located immediately below the fresh-air intake. The economizer assembly also included internal dampers to control the balance between the fresh air and the return air that is supplied back to the building.

Tests were conducted over a range of exhaust and intake air-flow rates from 1000 to 4000 CFM (472 to 1888 l/sec). Due to the close proximity of the exhaust to the intake, the re-entrainment of building-air exhaust was significantly greater than the entrainment of flue gas. The minimum dilution ratio was 9, corresponding to a re-entrainment of 11 percent of the building-air exhaust air. The minimum dilution ratio was independent of the flow rate of the exhaust and intake air streams. The minimum dilution ratio occurred at wind speeds less than 1 ft/sec (0.3 m/sec), and at very low levels of wind turbulence.

COMPARISON OF MINIMUM DILUTION RATIO PREDICTIONS WITH DATA

The method for predicting plume dispersion presented in the ASHRAE Handbooks was compared with the minimum dilution ratio measurements. The predictions for the downward facing vent agreed to within a few percent of the measurements. For the short vertical vent the predictions were about 35 percent lower than the measurements. Overall, the minimum dilution predictions provide a conservative estimate for these two cases.

The tall vertical vent extended above the top of the packaged HVAC unit by 10 inches (25 cm). Elevating the flue-gas exit above the top of the unit causes a significant reduction in flue-gas entrained into the fresh air intake. A procedure* was used for predicting the reduction in concentration at the intake due to increases in stack height and exit velocity. The result was used to modify the methodology given in the ASHRAE Handbooks. The modified prediction was within 35 percent of the measured data, and gave a conservative estimate of the dilution ratio for the tall vertical vent.

The predicted minimum dilution for the economizer mode did not compare well with the measured data. The analytical expressions in the ASHRAE Handbooks treat only two cases: a vertically directed, uncapped exhaust and a capped exhaust. The economizer exhaust is powered with an axial fan and passes through a set of gravity louvers. The gravity louvers and the exhaust hood provide damping of the exhaust, but not to the extreme of a cap over the exhaust. The exhaust characteristics of the economizer fall between the uncapped exhaust and the capped exhaust. The data fall midway between the predictions for these two extreme cases.

COMPARISON OF CFD RESULTS WITH MEASUREMENTS

Computational fluid dynamics (CFD) is becoming recognized as a viable tool for predicting external flow phenomena subject to atmospheric turbulence. In its application to atmospheric modeling the most relevant developments are in the areas of turbulence modeling. Atmospheric turbulence spans a large range of scales, from small-scale turbulence comparable to the mean free path of molecular motion, to large scale eddies and vortices comparable to the scale of the packaged HVAC unit. Turbulent diffusion models have been developed to capture this range of turbulence scales and to simulate the effect of turbulent transport on the flow field. In this study the standard k-ε model was used.

The CFD predictions of minimum dilution ratio of flue gases were obtained for the short vertical vent and the tall vertical vent. In both cases the CFD prediction was about 35 percent lower than the measured minimum dilution ratio, providing a conservative estimate of entrainment.

An effective means of increasing the dilution ratio of flue gases from a packaged HVAC unit is by increasing the height of the vertical vent outlet above the top of the unit. Raising the vent exit 10 inches (25 cm) above the unit was found to increase the dilution ratio by more than a

* Wilson, D.J., "Effect of Vent Stack Height and Exit Velocity on Exhaust Gas Dilution," ASHRAE Transactions, Vol. 83, pp 157167, (1977)

factor of two. Predictions made using CFD calculations indicate that the minimum dilution ratio increases exponentially for vent heights greater than 10 inches (25 cm). An additional increase of a factor of two in dilution ratio may be possible by raising the vent from 10 inches to 13 inches (25 to 33 cm).

In the economizer mode the CFD model over-predicted the minimum dilution ratio in most cases. In one case [North wind, 4000 CFM (1888 l/sec) building air exhaust] the prediction was very close to the measured minimum dilution ratio. Although the CFD results for the unit operating in the economizer mode do not agree with all the data, the minimum dilution ratio predicted was only 22 percent higher than the minimum dilution ratio measured.

The cause of the high dilution ratio predictions for the economizer may be related to the modeling of the building-air exhaust configuration. The CFD model treats the exhaust as an unrestricted flow with a high momentum. For the test unit the building-air exhaust is forced through a set of gravity louvers that deflect and diffuse the flow. This added turbulence and diffusion are not treated by the CFD model, and may result in less diffusion of exhaust gases. As was the case for the analytical predictions discussed above, the CFD results indicate that by removing or reducing the restrictions to the exhaust flow the dilution of building-air exhaust may be increased.

CONCLUSIONS AND RECOMMENDATIONS

Of the vent configurations tested, the tall, vertically-directed vent provided the greatest dilution of flue gases entrained into the fresh air intake on the packaged HVAC unit. The dilution of flue gases from the short vertical vent and the downward facing vent was three to four times lower than the tall vertical vent. The downward facing vent was least effective in diluting the flue gases prior to being entrained by the fresh air intake.

When operating in the economizer mode the minimum dilution ratio for exhausted building-air was 9, representing a re-entrainment of 11 percent of the exhausted gases. The minimum dilution ratio did not appear to depend on the exhaust and intake flow rates, and was not affected by the operation of the air conditioner.

The method of predicting plume dispersion in the ASHRAE Handbooks compared favorably with the measured data for the dilution of flue-gases. For the building-air exhaust measurements made in the economizer mode the predictions do not agree well with the data. However, these analytical expressions indicate that an unrestricted exhaust would provide greater dilution of exhaust gases.

The flow field about the packaged HVAC unit was modeled using CFD analysis to predict the dilution of exhaust flows. The CFD predictions were in good agreement with the analytical expressions given in the ASHRAE Handbooks. Compared with the measured data, the CFD analysis predicted 35 percent less dilution of flue gases than measured for the short and tall vertical vents, providing a conservative estimate of flue-gas dilution for the unit tested.

In the economizer mode the CFD model over-predicted the amount of dilution of exhaust gases for all cases considered. The lack of agreement is believed to be due to the restrictions in the exit of the economizer. As was found for the ASHRAE Handbook predictions, the CFD results also suggest that the dilution of exhaust gases can be increased by redesigning the exit configuration of the economizer to provide unrestricted flow of the building air exiting the unit.