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# New Rules For Kitchen Exhaust

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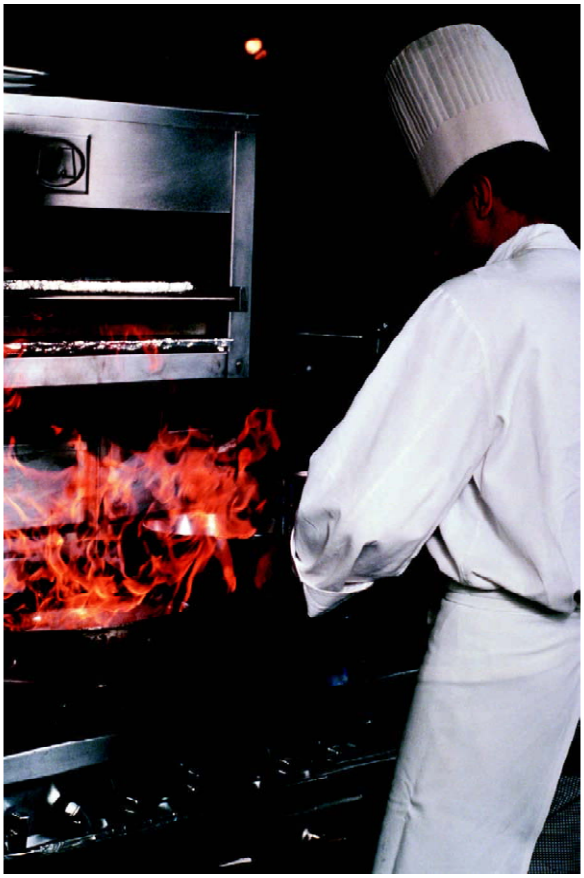
Commercial kitchen design professionals were concerned that the minimum exhaust air ductwork velocity of 1,500 fpm (7.62 m/s), as required by the National Fire Protection Association (NFPA 96[1]), was too restrictive. ASHRAE Technical Committee 5.10, Kitchen Ventilation, sponsored and provided project guidance for a recently completed research project, RP-1033, addressing the relationship between grease deposition and exhaust velocity. The research project not only resulted in several published documents,[2,3,4] but NFPA 96 reduced the minimum exhaust velocity to 500 fpm (2.54 m/s) in March 2002.



An ASHRAE research project led to a new NFPA exhaust velocity standard.

This article summarizes the study that influenced the change in NFPA 96 and presents examples of how to benefit from the less restrictive requirements while avoiding potential pitfalls.

Cooking effluent consists of vapors and particles. Previous experience[5,6] indicates that using real cooking processes to produce cooking effluent for measurement purposes is expensive, uncontrollable, and leads to highly variable emission rates. For this reason, the experimental approach to address grease deposition in exhaust ductwork is to measure particulate and vapor deposition rates separately using artificial cooking effluent. This allows control over the important parameters, resulting in an improved understanding of the deposition processes. From this information empirical models of the processes are developed. Actual cooking effluent measurements help validate the models for a limited "real-world" case (see sidebar on Page 30 for more information about the setup and procedure).

## Results

Deposition velocity is the fundamental parameter used to describe the rate at which particles deposit to a surface. It is analogous to a mass transfer coefficient and is calculated using *Equation 1.*

$$V_{dep} = N/C \qquad (1)$$

Where $V_{dep}$ is the deposition velocity, $N$ is the mass deposition flux, and $C$ is the particle mass concentration. For this investigation, the mass concentration was calculated using the measured aerosol concentration at the duct centerline. The mass deposition flux is calculated using *Equation 2.*

$$N = m/At \qquad (2)$$

Where $m$ is the particle mass deposited on the surface, $A$ is the surface area, and $t$ is the accumulated collection time. The deposition velocity is of practical use in comparing particle deposition in real-world applications where the aerosol concentration remains constant. For example, when a high emission kitchen appliance is replaced with a low emission appliance, and the total exhaust volume is reduced, the aerosol concentration can remain constant. Likewise, when designing a new exhaust system, it is possible to adjust the

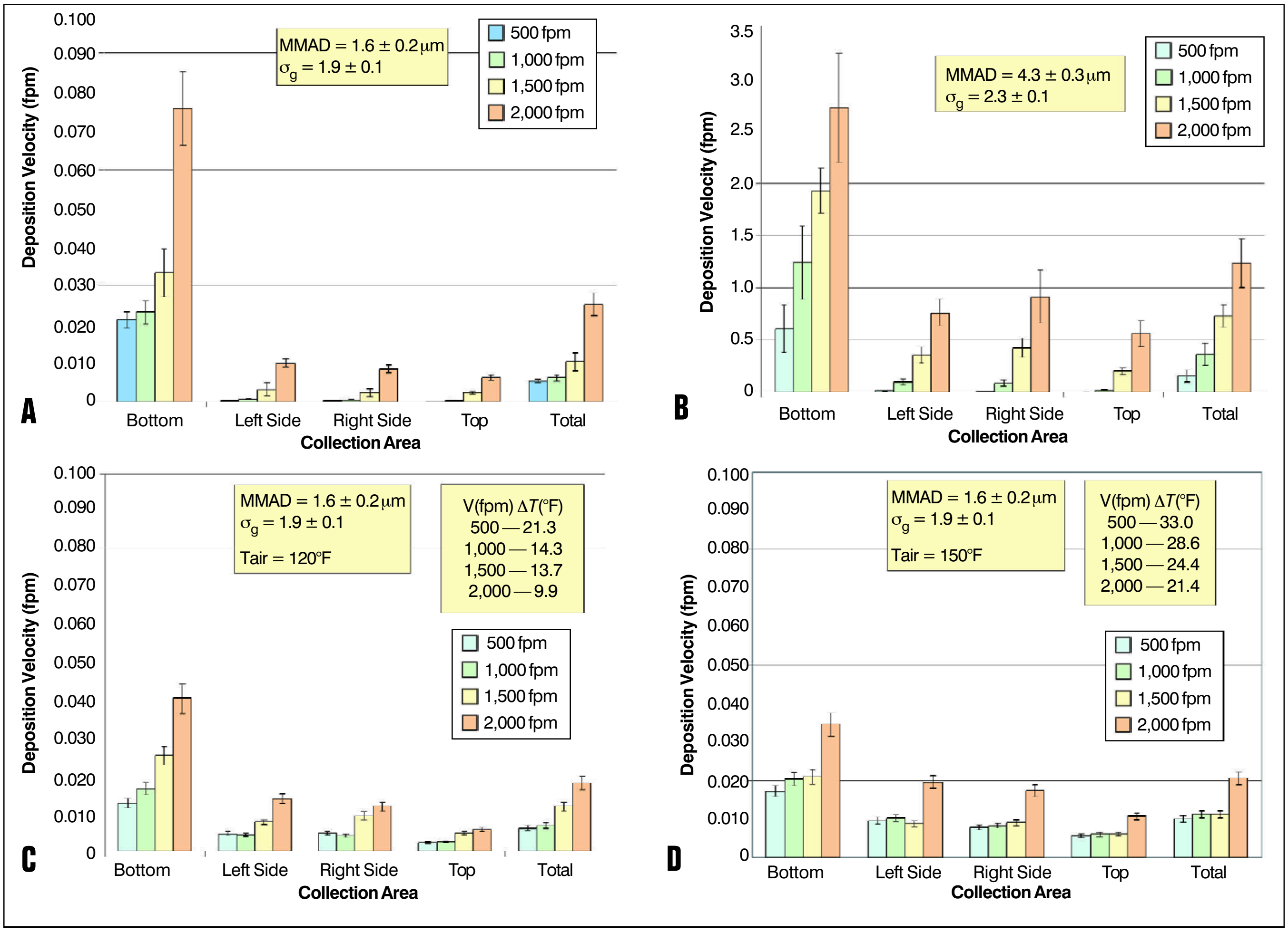


**Figure 1: Deposition velocity of polydispersed particles on the internal surfaces of a horizontal square exhaust duct vs. mean exhaust velocity. A) MMAD = 4.3μm, isothermal conditions B) MMAD = 1.6 μm, isothermal conditions C) MMAD = 1.6 μm, exhaust air temperature = 120°F (48.9°C) D) MMAD = 1.6 μm, exhaust air temperature = 150°F (65.6°C).**

duct size and corresponding volumetric flow rate while maintaining constant aerosol concentration.

Some applications have a constant aerosol generation rate that results in an increase in particle concentration when reducing the exhaust velocity. For instance, an appliance may be found to operate effectively with reduced exhaust volumetric flow rate while maintaining capture and containment. If the effluent emissions and exhaust duct size remains the same, the result will not only be a decrease in exhaust velocity, but a corresponding increase in particle concentration. Therefore, the deposition velocity is not the only parameter of interest; the rise in concentration in the exhaust also affects the particle deposition rate. Multiplying the deposition velocity by the concentration before and after a change in exhaust flow rate provides the mass flux to the wall in each case, which allows for quantitative comparison. For discussion purposes, the situation with constant aerosol concentration is referred to as Case I, and the situation with a constant aerosol generation rate is referred to as Case II.

In *Figure 1*, the ordinate is the deposition velocity while the abscissa shows the collection area of the duct. Measurements were taken on all four sides of the horizontal exhaust duct, thus the areas are designated top, bottom, and left and right sides. The overall average deposition also is shown. Each chart shows results from all four tested exhaust velocities. Isothermal results for two particle sizes, 4.3 and 1.6 μm are shown along with non-isothermal results for the 1.6 μm particles at 120°F and 150°F (48.9°C and 65.6°C) exhaust temperatures. The data are directly applicable to Case I.

For isothermal cases, it is clear deposition velocity decreases as the exhaust velocity decreases. This is true for both the horizontal surfaces (top and bottom) and vertical surfaces

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(left and right sides). The deposition is higher at the bottom surface and lower at the top surface due to the effects of gravitational settling. The sides are unaffected by gravitational settling. The other deposition mechanism at work is called turbulent aerosol deposition. Higher turbulence results in more particles "thrown" to the wall surface. Lowering the exhaust velocity does not affect gravitational settling, but does decrease turbulent deposition dramatically. The net result is a decrease in deposition. While not shown in the figure, similar results were found for the two smaller particle sizes, 0.95 and 0.49 μm.

Applying the result to Case II is more complicated. For vertical surfaces, the deposition velocity decreases much more rapidly than the particle concentration increases, thus there is still a significant decrease in deposition with decreasing exhaust velocity for all particle sizes tested. For the bottom surface, higher gravitational settling due to higher particle concentrations either cancels out the decrease in deposition velocity (largest particles), or begins to dominate (smaller particles). The net result for all internal surfaces of a horizontal duct is a reduction in deposition with decreasing exhaust velocity for the 4.3 μm particles, a constant deposition for the 0.95 and 0.49 μm particles, and a minimal value of deposition at about 1,000 fpm (5.08 m/s) with a slight increase as the velocity goes to 500 fpm (2.54 m/s) for the 1.6 μm particles. The magnitude of the mass deposition is much greater for the larger particles. When a wide size range of particles is present, the behavior of the largest ones will dominate the overall deposition. This suggests that in most cases, reducing the exhaust volume will either decrease aerosol deposition or not change it appreciably.

When the exhaust air temperature is elevated and there is an appreciable wall-exhaust air temperature difference, the phenomena of thermophoresis becomes an important deposition mechanism. Thermophoresis causes particles to migrate from hot to cold air temperatures due to uneven thermally induced collisions with gas molecules. The momentum from the hot side air molecules is greater than the momentum from the cold side air molecules and the particle moves towards the cold. The charts for the elevated exhaust air temperature (C and D) show that eventually thermophoresis begins to dominate particle deposition for Case I applications. However, even at the highest temperature difference tested, the deposition velocity does not increase for horizontal surfaces, but remains rather constant. When applied to Case II applications, deposition begins to increase with decreasing exhaust velocity, at the wall-exhaust air temperature differences tested. Therefore, the combination of increased particle concentration and thermophoretic effects increasing deposition overwhelms the effect of turbulent deposition effects decreasing deposition, with decreasing exhaust velocity.

It is important to comment on the tested wall-exhaust temperature differences and how likely they are to be experienced in the field. The temperature difference for all 10 cooking processes tested in a previous investigation[5] exceeded 2.1°F (1.1°C) for only the gas broiler and gas range. In this case, the exhaust duct was not insulated. Therefore, it is likely that many commercial cooking exhaust systems do not experience significant temperature differences even with non-insulated ducts.

Unlike particle deposition in turbulent airflow, turbulent vapor deposition is a well-understood and documented phenomena. Therefore, the results will not be presented here. It is sufficient to report the results confirmed the applicability of classic mass transfer theory. The theory predicts the transfer rate decreases with decreasing exhaust velocity and decreasing temperature difference between the exhaust air and the duct. In non-insulated ducts, the temperature difference will increase, increasing deposition, while the decreasing exhaust velocity decreases deposition. The net result will be an increase in deposition because the dependence on temperature difference is more pronounced. For insulated ducts, the vapor deposition will be negligible.

## Summary

The following general observations can be made:

Case I: Constant Exhaust Concentration and Temperature

The rate of grease accumulation decreases with reduced exhaust velocity regardless of the duct orientation and insulation level.

Case II: Constant Effluent Generation Rate, Variable Concentration in Exhaust

a) Well insulated ducts, R-10 h ft$^2$ °F/Btu (1.8 m$^2$ °C/W) and higher,

The rate of grease accumulation decreases with reduced velocity regardless of duct orientation.

b) Uninsulated ducts,

Here the results depend on the specific conditions. For high velocities, the rate of total grease deposition will decrease with a reduction in velocity when the particle deposition dominates, but will increase for all other conditions.

## Discussion and Application of Results

Three scenarios are presented using the results generated in this investigation. The idea is to guide the designer and user of kitchen exhaust duct systems regarding the influence of exhaust velocity on the rate of grease accumulation in the straight sections of an exhaust duct.

A. Consider a situation in which a current exhaust system runs continuously at 1,500 fpm (7.6 m/s) regardless of the amount of effluent generated. Assume that the effluent generation consists of periods of full load and periods where a minimal amount is generated. What is the impact of reducing the exhaust velocity during the periods of very light load?

The majority of the grease deposition will occur during full-load operation. A negligible amount will occur during the

# Setup and Procedure

Measurements are made in a 10 by 10-in. (254 by 254-mm) square exhaust duct made of welded black iron. Exhaust velocities are controlled by a variable speed fan and include 500, 1,000, 1,500, and 2,000 fpm (2.54, 5.08, 7.62, and 10.16 m/s). Two duct heaters allow the control of test exhaust temperatures at ambient, 120°F (48.9°C), and 150°F (65.6°C). Particulates are introduced 15-ft (4.57 m) upstream of the test measurement section using an aerosol generator. The schematic of the test setup is shown in *Figure 2*.

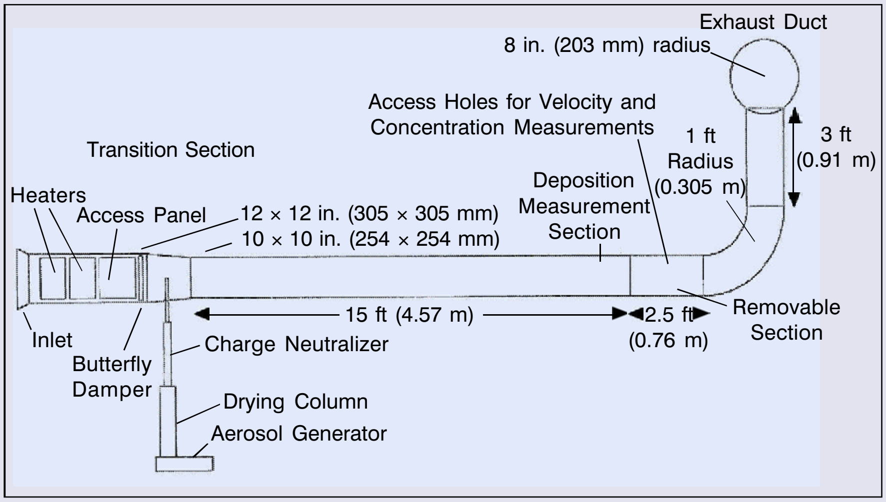

**Figure 2: Schematic diagram of the test duct.**

For particulate generation, oleic acid is tagged with uranine, a florescent dye, and mixed with various amounts of isopropyl alcohol and DI water. The solution is sprayed through a spray jet atomizer, resulting in polydispersed test aerosols with mass median aerodynamic diameters (MMAD) of 0.49, 0.95, 1.6, and 4.3 mm, depending on the amount of volatiles in the solution. Oleic acid is appropriate because it is often found in real cooking effluent. For example, it was found to be the most prevalent fatty acid in beef patties,[5] and olive oil is 85% oleic acid.[7] Uranine enhances the deposition measurement by at least three orders of magnitude over direct weighing. The technique is widely used and well documented in aerosol deposition studies.[8] The range of particle sizes associated with each MMAD is characterized by the geometric standard deviation ($\sigma_g$). The spray jet atomizer produces $\sigma_g$ values from 1.8 to 2.3, the same values found in cooking emission characterization studies. [5,6]

The deposition of the particles is measured using 0.004 in. (0.102 mm) stainless steel shim stock attached to the inner duct walls. After testing, the shim stock is carefully removed, wiped down with isopropyl alcohol pads, and the pads placed in a 0.0011 N solution of NaOH and DI $H_2O$. The solution is sonicated, allowed to settle, and the mass of uranine determined fluorometrically. It should be noted the airflow velocity, temperature, and aerosol concentration is fully characterized for each test. These procedures are briefly explained in a paper[4] and explained in detail in the research project full report.[2]

Using well-documented techniques in the heat transfer literature, the grease vapor mass transport rate is determined by measuring the evaporation rate of a volatile fatty acid from the duct wall into the exhaust airflow. It is easier to establish well-characterized boundary conditions, in which the vapor is transported from the duct wall into the airflow, than the usual case in kitchen exhaust ducts where the vapor flows towards the wall surface. The magnitude of the mass transport coefficient is not affected by this change in transport direction. Octanoic acid was chosen as the fatty acid because of its high vapor pressure and presence in many vegetable oils and butter. It is applied to substrates located on the bottom of the duct test section. A calibrated electric heater maintains the oil at a constant temperature. The change of weight of the substrate during each test is used to determine mass transport. The procedure includes an experimentally determined correction for evaporation due to initial weighting, mounting time, preheat and post cooling, and final weighing procedures.

For the actual cooking effluent test, a small commercial cooking electric broiler is used to cook ground beef patties. The food product specifications and cooking procedures are specified in ASTM F-1695-96.[9] The same procedures used to characterize the effluent concentration, airflow, and deposition for the particulate study are used for the actual cooking effluent test. However, the cooking effluent is not tagged with a fluorescent dye; therefore, deposition is measured gravimetrically. Please refer to the full report for complete documentation of the test setup and procedures.⬢

periods of light load regardless of the exhaust velocity. Thus, the value of the exhaust velocity during periods of light load has a negligible effect on the total grease buildup and could be varied to capture and contain the effluent without regard to the rate of grease buildup in the duct. The operating cost will be dramatically reduced if there are significant downtimes. Savings not only come from less fan energy, but a reduced load for the makeup air system.

B. Consider a situation where the effluent is generated during three periods; full load, two-thirds full load and one-third full load. Assume that the effluent is identical, only the quantity changes (e.g. using three, two, or one broiler respectively to cook beef patties). The exhaust velocity is currently set at a constant value of 1,500 fpm (7.6 m/s). Consider the effect of grease accumulation in the existing duct if the velocity is reduced to 1,000 fpm (5.1 m/s) during the two-thirds full-load operation and to 500 fpm (2.5 m/s) during the one-third full-load operation. Assume that the reduced velocity is adequate for capture and containment so the only concern is the grease accumulation rate in the exhaust duct.

This is an example of a Case I situation where the exhaust concentration and temperature differences remain constant, but the mean velocity changes. The rate of grease deposition will decrease compared with the case of constant velocity for all conditions. The rate of particle deposition decreases and the rate of vapor deposition decreases for all duct configurations, horizontal and vertical, insulated or not. Again, operating cost savings could be significant.

C. Consider a situation in which the effluent generation is constant and the current operation is to maintain the exhaust velocity at 1,500 fpm (7.6 m/s). How will the grease deposition rate change if the velocity through the existing duct system is reduced to 1,000 fpm (5.1 m/s)? Assume that capture and containment can be achieved with the reduced velocity. Therefore, the grease deposition rate in the duct is the only concern.

Here the effluent generation rate is constant as the velocity is varied so this corresponds to an example of Case II. The concentration of particles and grease vapor increase as the exhaust velocity decreases. The results depend on the amount of duct insulation.

i. Well insulated duct, R-10 h ft$^2$ °F/Btu (1.76 m$^2$ °C/W) or higher.

The vapor deposition rate is negligible, and the particle deposition rate decreases with the reduced velocity so the rate of total grease deposition decreases with reduced velocity for all duct orientations.

ii. Uninsulated duct,

The particle deposition rate decreases but the rate of vapor deposition increases. The net effect depends on the ratio of particle to vapor deposition. In most cases, the particle deposition rate is expected to dominate so the total deposition rate will decrease or increase slightly as the velocity is reduced. If the velocity is further reduced to 500 fpm (2.5 m/s), the particle deposition rate may increase compared to the 1,000 fpm (5.1 m/s) velocity because thermophoresis begins to dominate. Therefore, the total rate of grease accumulation is expected to rise. The reader is referred to the model and example calculation presented in the full report[2] to quantify the expected deposition.

Scenario C has the greatest potential for problems arising from improper application. For instance, a restaurant in Minneapolis may operate an exhaust system that is determined to capture and contain effluent sufficiently at 50% of the current flowrate. However, the exhaust velocity is 1,500 fpm (7.62 m/s) and until recently, a reduction was not allowed. With the new standard it is possible to reduce the velocity to 750 fpm (3.81 m/s). However, at this restaurant, the exhaust exits the building immediately into a non-insulated exhaust duct running outside the building. Due to the cold climate, the temperature difference between the exhaust air and wall would be significant, and would increase with a decrease in exhaust velocity. The result would be an increase in both vapor and particle deposition. It is likely that the restaurant already has grease buildup problems at 1,500 fpm (7.62 m/s), especially in midwinter. Reducing the exhaust velocity would compound this. The best solution would be to insulate the duct.

## Other Considerations

The results presented are applicable to straight rectangular or round ductwork. Only when a high aspect ratio horizontal duct is used would we expect significantly different results (due to an increased surface area for gravitational settling). Of more significance is the effect of bends, elbows, or other non-straight ductwork, which usually are present in exhaust systems. The vapor deposition will remain unchanged flowing through these regions. It is expected that the particle deposition will decrease significantly with decreased exhaust velocity. The explanation is particle deposition in a bend is dominated by inertial impaction. Inertial impaction is a function of velocity and decreases with decreasing velocity. During the actual cooking tests, a substrate was placed on the inner surface of the 90-degree bend, downstream of the test section. The results show less deposition at lower velocities. Therefore, while testing exhaust velocity effects in elbows and bends was beyond the scope of the ASHRAE research project, there is strong theoretical evidence, and some experimental evidence, that a reduction in velocity decreases grease deposition.

Finally, all examples assume that effluent capture and containment is satisfied and the minimum velocity for the grease removal device is met when the exhaust volume is reduced. In practice this a critical element and airflow reduction should only be considered if the exhaust hood properly captures and contains at the new flow rate. If the velocity required for the grease removal device cannot be met with the lowered exhaust volume, one can reduce the effective area of the grease removal device, proportionally increasing the velocity. For instance, with baffle filters, blanks are often available, and can be placed in an area of the hood with minimal direct contact with effluent.

## Conclusions

An experimental investigation of exhaust velocity effects on grease deposition in kitchen exhaust ducts has influenced changes to the NFPA 96 minimum exhaust requirement. The requirement has been reduced from 1,500 fpm (7.6 m/s) to 500 fpm (2.5 m/s). The new standard maintains or improves the safety aspect of minimizing grease build-up, while allowing engineers more flexibility in both retrofit and new kitchen design, including variable flow kitchen exhaust. For many applications, a reduction in exhaust velocity will be beneficial. In some cases, lowering the exhaust velocity can increase grease deposition and the design professional should be careful to identify these situations. Lowering velocity reduces grease deposition in virtually all cases when ductwork with insulation of R-10 or greater is used.

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