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Abstract

A probabilistic analysis with the American Gas Association Research Division model and Crystal BallTM determined the contribution of vent-free gas appliances to total indoor relative humidity (RH). At least 20,000 simulations were conducted for each DOE Heating Region. Vent-free heating contributed to average indoor RH as little as 4% for DOE Region I, to up to 43% for Region V across all scenarios. The great majority of cases in all DOE regions were associated with RH levels from all indoor water vapor sources that were less than the 70% RH concern level for active mold and mildew growth. © 2004 Elsevier Ltd. All rights reserved. keywords: Indoor humidity; Gas appliance; Stochastic modeling; Mold and mildew

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l. Introduction

Over 12 million consumers use vent-free gas heating products, which provide safe, clean, efficient heat without the need for a vent. The term "vent-free gas product" is used here to mean all types of vent-free products ("yellow flame", "blue flame", "infared plaque", and "hearth" vent-free products), including plaque heaters, gas logs, fireplace systems, and free-standing gas heating stoves. Because combustion of natural gas or propane in a vent-free device produces water vapor in the home, questions have been raised regarding the possible contribution of vent-free gas products to mold and mildew problems in the home.

There are many sources of water vapor in indoor residential settings, including appliances (e.g., automatic dishwashers, clothes driers), human activities (e.g., showering, cooking), human breath, water vapor from outdoor air, and water infiltration into the home (e.g., plumbing leaks, roof leaks, gutter overflow, infiltration into basement). The relationship of indoor relative humidity (RH) to indoor sources of water vapor, outdoor RH, and building factors (e.g., air exchange rates, heat exchange) is complex. RH is defined as the percent saturation of air with water vapor at a given temperature; the warmer the air

the greater is the mass of water per cubic meter required to achieve a given RH level [1]. The American Society of Heating, Refrigerating, and Airconditioning Engineers (ASHRAE) has recommended an indoor RH range of 40-60% as being desirable based on comfort. The US Environmental Protection Agency has recommended a range of 30-60% for indoor RH based on comfort. During the heating season, when cold "dry" air is brought into the home via normal infiltration/air exchange, supplemental humidification may be required to achieve these levels of indoor humidity [2]. Indoor environments are abundant in a variety of mold and mildew species, including Penicillium, Aspergillus, Cladosporium, and Fusarium species [3-5]. Factors such as the presence of a basement, no central air conditioning, or decreased use of air conditioning are associated with elevated levels of fungi in homes. This suggests a strong link between mold and mildew growth with elevated indoor RH. Moisture is required for mold spores to germinate [6]. Indoor air levels of fungi are highly variable, but total counts indoors in non-problem homes average about 40-50% of outdoor counts [7]. Controlling moisture in the residence is the one way to control mold growth. A RH level of 70% or greater can result in rapid growth of mold and mildew [8]

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Surface counts of Penicillium glabrum inoculated onto ceiling tiles were 2000-4000 times higher at 97% RH compared to counts occurring at 54% RH [9]. Kalliokoski et al. [10] identified a RH range of 75-80% as the threshold for supporting active growth of mold and mildew on a variety of building materials, including wallpaper, gypsum board, wood, plywood, and acoustical fiber board. The ASHRAE standard for indoor RH is 40-60%, based on comfort. The USEPA has set <60% indoor RH as a goal for mold and mildew control, and has set 70% indoor RH as a level of concern above which significant mold and mildew growth may occur. In the mid-1990s, the American Gas Association Research (AGAR) Division developed an indoor air quality model [11] that simulates how indoor air quality varies with time in a well-mixed space heated by a vent-free gas appliance in each of the DOE heating regions (see Fig. 1).A conceptual overview of the model is shown in Fig. 2. One of the model outputs is the time profile of the indoor RH in the room where the vent-free appliance is used.The model considers a number of parameters, including heat losses from the ceiling, walls, and floor in the room where the vent-free heating device is used;the volume of the room; the size of the connected space immediately outside the room (e.g., hallway or another room)

that provides immediate dilution volume for combustion products; the air exchange rate; house volume; outdoor temperature; and outdoor humidity. Heat losses to indoor air include energy required for heating cold infiltrating outdoor air; energy losses conducting through exterior walls, floor, and ceiling; and heat accumulated by sinks such as ceiling, floor. and furniture during the ON cycle of the device. The heat sources accounted for by the model include the gross input rate minus the latent heat of combustion (during the ON cycle) and heat accumulated by interior surfaces (during the OFF cycle). The vent-free model considers all additional sources of water vapor in the home, including human breath, cooking, showering, and washing dishes and clothes. The model assumes that the vent-free heater and people in the room of product use contribute water vapor directly into the room, whereas water vapor from other sources are assumed to be diluted into the whole house volume. The model was validated at the AGAR research home in Cleveland and the GRI research house in Chicago [11], and was determined to perform well in predicting the time profile and equilibrium level of indoor RH associated with the use of vent-free gas products for supplemental localized residential heating.

Table 1.

Parameter ranges used in stochastic modeling of total indoor relative humidity with and without the occurrence of a vent-free gas heating device

Model parameter

Range of values

Comments
References

Room volume

a1400-4000 ft3

Based on NAHB Survey

[12]

House Volume

b8000-48,000 ft3

Based on NAHB Survey

[12]

Outdoor relative humidity

c50-90%

1971-2001 winter data

[13]

Outdoor temperature

d1000 h winter outdoor values

DOE Region-specific

[11]

Indoor temperature set pt.

72°F

Model run at 72 ± 1 °F

Air exchange rate

e0.35-1.0 ACH

Range used in GRI 1996

[11,14]

Number people in room

1, 2, 3, or 4

Max. of four from GRI 1996

Number of external walls

1, 2, or 3

Input rate

10,000-40,000 Btu/h

Reflects product diversity

Heat loss factors (U)

Walls: 0.636-1.34 W/m2 °C

Representative ranges across loose,

Floor: 0.137-0.778 W/m2 °C

average, and tight homes (GRI 1996)

Ceiling: 0.261-0.778 W/m2 °C

Connected volume

1/2(Room volume) to 1/2(House volume)

Assumed to be zero for isolated rooms f

Combustion water vapor

0.00362 kg/kW/s

From normal cycling of vent-free product

[11]

Human water vapor

0.0000126 kg/person/s

From breath of people in room of product use

[11]

Other water sources

g 0.0-0.0000687 kg/s

[11]

a Equivalent to range of values for typical living room.

b Equivalent to 1000-6,000 ft2 homes, assuming an 8 ft ceiling height.

c Range encompasses monthly average minitnuan to monthly average maximum across all DOE regions during winter.

d The 1000 h temperature for a given the DOE region indicates that there are 1000 h in the heating season when the outdoor temperature is below that temperature value; specific values include 56°F for DOE Region I; 45°F for DOE Regions II and VI; 36°F for DOE Region III; 26°F for DOE Region IV; and 13°F for DOE Region V

e This range corresponds to the 30th-90th percentile winter season air exchange rate nationally [l4]; a minimum of 0.35 air changes per hour (ACH) was chosen because building codes typically require mechanical ventilation below this level.

f An isolated room is defined as a room of vent-free product use where the door to an adjacent room or house space is closed.

g Time-averaged rate representing contributions of other appliances (e.g., dishwasher, clothes washer, dryer) and human activities (e.g., cooking, showering); minimum of zero is value for isolated rooms; maximum shown is scaled to a household of four people (approximately 1.5l/person/day).

2. Methods

The BASIC computer program VENTFI.BAS [11] was converted to an Excel spreadsheet for ease of use. This converted program and Crystal BallTM 2000 were loaded onto a modeling platform known as NOTITIA. An initial sensitivity analysis was conducted to deter-mine the impact of the heat input rate (of the vent-free appliance), set-point temperature, room volume, number of walls with external contact, and size of interconnected volume on indoor RH in the room in which the vent-free gas heating product is used. This sensitivity analysis was conducted under conditions for DOE Region IV. Probabilistic runs were conducted for each DOE Region, using the NOTITIA-mounted AGAR model and Crystal Ball® 2000, based on ranges of values for each of the key parameters as indicated in Table 1. Because information on the exact distribution forms for each of the input parameters was not available, uniform

distributions were assumed for most of the parameters (values for parameters such as outdoor temperature and indoor temperature set point were fixed). Input parameter distributions were sampled at random and the vent-free gas appliance model was run for the randomly selected set of parameter values. This process was repeated at least 20,000 times to fill out the output distribution for each DOE region. This effort was conducted with and without the vent-free appliance emission included in order to determine the relative contribution of vent-free gas heaters to total indoor RH. The water vapor emission characteristics of the product were estimated based on combustion chemistry. Values obtained were subjected to a 95% confidence test to remove outliers resulting from unlikely combinations of parameter values. The statistical output from each of the probabilistic runs included the mean, 90th percentile, maximum, and percent of cases less than 60% or 70% indoor RH.

3. Results

3.1 Sensitivity analysis

The model output, which includes the time profile of indoor RH, reflects the anticipated ON/OFF cycling during use of a thermostatically controlled vent-free gas product. As part of the sensitivity analysis, using rated input rates of 10,000, 20,000, or 40,000 Btu/h, it was determined that the time profiles of RH in the room of use are identical, regardless of rated input when all other parameter values are held constant. The influence of temperature set point for the vent-free gas heater, examined for fixed parameter values in DOE Region IV for a 40,000 Btu/h gas heater at 69°F, 72°F, or 75°F, showed decreasing indoor RH with increasing set point. Varying room volume while holding other parameters fixed resulted in an apparent trend of decreasing indoor RH with increasing room size. For example, doubling, the room volume from 1000 to 2000 ft3 resulted in a 13% reduction in indoor RH in the room of use. Also, varying tile number of walls with external contact to outdoor conditions, while keeping other parameters fixed, indicated an increase in indoor

RH in the room of product use as the number of walls with outdoor contact is increased from 1 to 2 to 3 (with the remainder of the walls of the room having contact only with adjacent indoor rooms having no heat loss). The quantitative impact on indoor RH of decreasing the number of walls with external contact by I was equivalent to that of doubling the room volume (13% reduction). Varying connected volume while keeping all other parameter values fixed indicates that the greater the connected volume, the lower the indoor RH in the room where the vent-free gas product is located. For example, increasing the connected volume from one-fourth the size of the room to one-half the size of the room results in a 12% decrease in indoor RH in the room of product use. Varying, the number of people in the room of product use while keeping all other parameters fixed showed a similar magnitude of impact of human breath on indoor RH.

3.2. Stochastic analysis

Frequency histograms for indoor RH for combined cases (i.e., including isolated and non-isolated rooms) are shown for the various DOE regions in Fig. 3. The distribution form for Region I is approximately "beta" in appearance when the distribution is filled out to N = 50, 000 iterations. The distribution form for indoor relative humidity in the room where the vent-free gas heater is used becomes distinctly more skewed as the DOE 1000 h heating temperature decreases (e.g., for colder regions such as DOE Regions IV and V). The numerical results of the probabilistic analyses for combined cases are shown in Table 2. With all source of water vapor in the residence considered, the arithmetic mean total indoor RH in winter was less than 50% for all DOE regions. In 90% of all simulated cases, the total indoor RH in winter was less than 60% for all DOE regions. The maximum total indoor RH in winter with all sources considered was less than 60% for DOE Regions II-V. In DOE Region 1 (Florida and the Gulf Coast), approximately 95% of all simulated cases resulted in a total indoor RH of less than 60%, and 99.9% of all simulated cases were associated with a total indoor RH of less than 70%. Simulation sets with and without the vent-free appliance indicated that the vent-free appliance would contribute only 4% of the mean indoor RH in DOE Region I; 11% of the mean indoor RH in DOE Region II; 18% of the mean indoor RH in DOE Region III; 29% of the mean indoor RH in DOE Region IV; and 43% of the mean indoor RH in DOE Region V. The results for worst-case scenarios where simulations were conducted only for isolated room cases (i.e., rooms with interior doors closed to effectively eliminate interconnected airspace to adjacent rooms) indicate that the average total indoor RH was near or less than 60% for all DOE regions (see Table 3). Approximately 95-98% of the simulated isolated room cases were associated with an indoor RH of less than 70% in DOE Regions II-V. In the case of Region l, approximately 80% of the isolated room cases were associated with an indoor RH of less than 70%. Because it is assumed that water vapor from other water sources in the house have effectively no access to isolated rooms, the percent contribution of vent-free gas appliances to total indoor RH in isolated rooms is greater than in non-isolated rooms, specifically 14% in DOE Region 1; 26% in DOE Region 11; 36% in DOE Region III; 47% in DOE Region IV, and CO% in DOE Region V.

Table 2.

Results of the probabilistic analysis for combined cases (all possible connected volume values) using vent-free model a

DOE region

Outdoor temperature (F)b
Outdoor humidity range (%) c
Vent-free appliance present?
Other water sources present?
Indoor relative humidity (%)
Percent of cases <60% relative humidity
Percent of cases <70% relative humidity

Mean
90th percentile
Maximum

I
56
50-90
YES
YES
47.2
57.2
76.3
95.3
99.9

NO
YES
45.2
54.5
66.8
99.1
100

% Contribution of vent-free appliance to total indoor RH

4.2
4.7
12

II
45
50-90
YES
YES
35.7
43.5
59.3
100
100

NO
YES
31.9
38.7
49.5
100
100

% Contribution of vent-free appliance to total indoor RH
11
11
17

III
36
50-90
YES
YES
29.1
36.5
51.6
100
100

NO
YES
24.0
29.4
45.6
100
100

% Contribution of vent-free appliance to total indoor RH
18
19
12

IV
26
50-90
YES
YES
23.6
31.9
46.3
100
100

NO
YES
16.8
21.1
35.9
100
100

% Contribution of vent-free appliance to total indoor RH
29
34
22

V
13
50-90
YES
YES
19.6
29.1
43.5
100
100

NO
YES
11.2
15.1
29.2
100
100

% Contribution of vent-free appliance to total indoor RH
43
48
33

a Based on 20,000 simulations per run.

b Based on 1000 h heating temperature.

c Rounded range that encompasses the average monthly minimum to the average monthly maximum outdoor relative humidity for the period November through February for all five DOE regions (i.e., DOE Regions I-V), based on 30-year climatological data [13].

4. Discussion

The contribution of vent-free gas heating products to the total indoor RH in residences in the US has been addressed through the research described in this paper. The use of stochastic methods has allowed assessment of the RH impacts for a wide range of house scenarios. Prior work [11] indicated that because of the dynamic nature of air exchange and air movements in a house, airborne concentrations of combustion products from vent-free gas appliances level off in the room of product use after just a few hours of operation, and an equilibrium value of RH is attained and held until conditions change or the vent-free product is turned off. A 1995 survey of adult users of gas hearth products in British Columbia, Canada found that 96% used their gas hearth products for 4 h or less per usage [11]. A 1998 survey of gas log users in California showed an average use time of 2.8 h, with 77% of the usage being for 4 h or less [16]. Thus, our analysis, which is based on an equilibrium RH established after 4-6 h of product use, probably overestimates RH impacts for average uses, which are shorter in duration. An initial sensitivity analysis conducted for Region IV found that varying the appliance input rate (Btu/h) has no impact on the predicted indoor RH. This suggests that a smaller-rated vent-free appliance will be "ON" more than a larger-rated vent-free appliance, but that the same amount of fuel will be consumed, as driven by heat losses from the room and other factors. Sensitivity analyses on set-point temperature indicate that as the set point is raised (e.g., from 72 to 75°F), the predicted indoor RH in the room of product use decreases. This may reflect that the capacity of air to hold water increases rapidly with increasing temperature, offsetting the RH impacts of additional water vapor emissions at the higher set point, resulting effectively in a lower RH at increased temperatures. This finding is consistent with a monitoring study by Wilson [16], in which the indoor RH in nine of 10 California test homes decreased as temperature increased in rooms in which vent-free gas logs were operating (the RH in the remaining home stayed constant). In the sensitivity analysis, it was also noted that there was an apparent trend of decreasing indoor RH with increasing room size, which may be related to decreasing surface area to room volume ratio as room volume increases, resulting in a lower total heat loss for the ceiling/floor/wall area.

There also appeared to be an increasing indoor RH with increasing number of walls in the room of product use with contact with the outdoors, which probably directly reflects the impact of increasing heat loss on increasing fuel consumption and increasing water vapor production from gas combustion. Connected volume was also an important factor affecting the indoor RH in the room of product use - the greater the connected volume (e.g., adjacent hallway or open space) available for immediate dilution of combustion emissions, the lower the indoor RH in the room where the vent-free gas product is located. Based on the results of the stochastic analyses for combined cases, essentially all simulated cases reflect a total indoor RH that was below levels associated with active growth of mold and mildew. The percent contribution of a vent-free appliance to the mean total indoor RH decreases with increasing outdoor temperature (1000 h temperature) as one moves from the colder DOE regions (e.g., Region V) to warmer DOE regions (e.g., Region I). That 100% of the simulated combined cases in DOE Regions II-V, and 95% of the cases in Region I were associated with a total indoor RH less than 60% indicates that, under normal use conditions, ASHRAE and USEPA indoor RH guidelines will be met. That 95-98% of all simulated cases for isolated rooms in all but DOE Region i are associated with an indoor RH of less than 70% suggests that aggressive mold and mildew growth will be unlikely to occur even for these more confined uses. The lower RH impacts associated with interconnected space adjacent to the room of use suggests that simply leaving an interior door open between the room of product use and the remainder of the louse will reduce RH impacts for essentially all cases where the product is used in houses with normal air exchange rates, with the possible exception of DOE Region I. The higher modeled indoor RH values in DOE Region 1 appear to be largely attributable to the higher mass of water occurring in outdoor air at the relatively warm outdoor winter temperatures in DOE Region I. However, vent-free gas heaters make little contribution to total indoor humidity in DOE Region 1 because these devices will not be operating frequently due to warmer outdoor winter temperatures in this region that place little demand on the units. Further, the upper quartile range of the indoor relative humidity distributions for isolated rooms represents extreme examples of extreme cases, and must be interpreted with caution.

Table 3.

Results of the probabilistic analysis for isolated rooms with no connected space, using vent-free model a

DOE region
Outdoor temperature (F°)b
Outdoor humidity range (%) c
Vent-free appliance present?
Other water sources present?d
Indoor relative humidity (%)
Percent of cases <60% relative humidity
Percent of cases <70% relative humidity

Mean
90th percentile

I
56
50-90
YES
NO
62.0
74.7

43.7
80.4

NO
NO
53.6
66.5

75.5
94.7

% Contribution of vent-free appliance to total indoor RH
14
11

II
45
50-91
YES
NO

54.6
65.5

75.9
94.6

NO
NO
40.6
51.9

97.3
99.6

% Contribution of vent-free appliance to total indoor RH
26
21

III
36
50-90
YES
NO
51.6
62.5

85.0
97.0

NO
NO
32.8
43.3

99.4
100

% Contribution of vent-free appliance to total indoor RH
36
31

IV
26
50-90
YES

NO
49.4
61.8

87.3
97.7

NO
NO
26.2
36.4

99.9
100

% Contribution of vent-free appliance to total indoor RH
47
41

V
13
50-90
YES
NO
51.0
62.8

84.5
96.6

NO
NO
20.2
29.3

100
100

% Contribution of vent-free appliance to total indoor RH
60
53

a Based on 20,000 simulations per run.

b Based on 1000 h heating temperature.

c Rounded range that encompasses the average monthly minimum to the average monthly maximum outdoor relative humidity for the period November through February for all five DOE regions (i.e., DOE Regions I-V), based on 30-year climatological data [13].

d For isolated rooms, human breath and outdoor humidity are sources of water; "other" sources (e.g., from showering, cooking, laundry, dishwashing) are assumed not to be present because the room in which the vent-free is used is closed off from the remainder of the house

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