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MASS AND FANS IN ATTACHED SUNSPACES*

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ABSTRACT

The effect of thermal storage mass on the performance of an attached sunspace is investigated for a particular design in Boston. Mass in the sunspace and in the adjoining building are compared. Performance is evaluated in terms of temperature conditions in the sunspace and delivery of useful solar heat to the adjoining building. The dependence of the results on the manner of heat delivery is studied. Both natural convection and fan-forced air flow are included.

1. INTRODUCTION

The presence of thermal storage mass in passive solar heating systems is always an important feature. The mass moderates temperature variations and provides stored heat for use at night and during cloudy days. Yet how effective the mass is depends on the details of how the mass is coupled to the solar heat and to the occupied spaces. In an attached sunspace, we want to know (1) how much mass should be in the sunspace, (2) how much mass should be in the adjoining building, and (3) how heat should be delivered from the sunspace to the building.

The customary answer is conditioned on whether the only purpose of the sunspace is to provide solar heat to the adjoining building or whether the sunspace is also used as living space or as a greenhouse for growing plants. It is often said that thermal storage mass in the sunspace is advisable only in the latter case to limit temperature extremes, but that the mass will reduce the ability of the sunspace to deliver solar heat to the adjoining building. In the case of a lightweight sunspace intended primarily as a solar heater, it is further said that use of a fan is advisable to transfer heat from the sunspace to the building because otherwise the sunspace will overheat and exhibit poor efficiency as a solar collector. There is a certain amount of plausibility to these claims about the role of mass and fans in a sunspace, but it is an uncomfortable situation that there is rather little supporting quantitative evidence. The purpose of this paper is to present the results of some calculations done to investigate the role of thermal storage mass and the means of heat delivery in an attached sunspace.

The key questions are the following: to what extent and under what circumstances does mass in the sunspace reduce the passive solar heating performance, and to what extent and under what circumstances does the use of a fan improve the performance? These are serious questions because they imply two unfortunate tradeoffs. First, if mass in the sunspace has an adverse effect on solar heating performance, there is a fundamental incompatibility in the design requirements of a sunspace that is capable of both a solar heating and a living or plant-growing function. The level of thermal storage mass would always be a compromise between these two functions. Second, if a fan is needed to maximize the solar heating performance of a sunspace, a designer is always in the position of balancing the solar heating advantages of the fan against the cost, absence of power consumption, reliability, and aesthetic advantages of passive heat delivery.

Some specialized terminology, such as load collector ratio (LCR), projected area, and solar savings fraction are used to describe the assumptions and results. Definitions of these terms can be found in Ref. (1).

2. THE CALCULATIONS

2.1. The Assumptions

The sunspace/building system definition has been narrowly confined to a particular location, sunspace design, and building

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load. The generality of the conclusions is accordingly very limited. The assumed geometry is shown in Fig. 1.

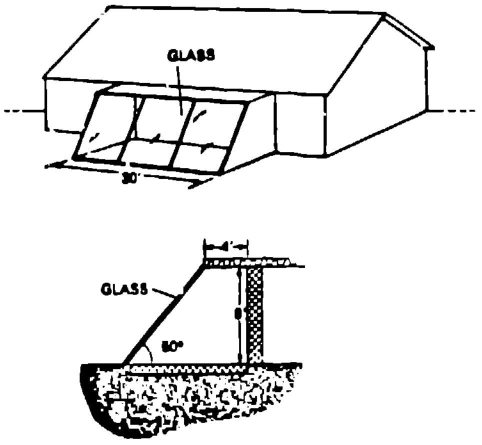

Fig. 1. Sunspace Geometry.

Other assumptions are summarized below.

Location	Boston
Load collector ratio	20 Btu/°F day ft^2
Sunspace	Double glazing Due south orientation Opaque end walls 6-in. concrete floor slab
Common wall	Lightweight R-20 insulation Backdraft dampers

Other sunspace and building characteristics that relate to heat storage capacity and heat distribution are varied in the study. Heat storage capacity, other than the sunspace floor slab, is assumed to be in the form of water in containers with a surface-to-volume ratio equal to that of 18-in. cylinders. The heat capacity is varied from 0 to 100 Btu/°F ft^2 of projected area in both the sunspace and the adjoining building. Unless otherwise noted, the sunspace and building heat capacities are fixed at 60 and 30 Btu/°F ft^2 of projected area, respectively, while other parameters are varied. The building mass is coupled only indirectly to solar radiation by means of natural convection from the building air and longwave radiation from interior walls. The results should be applicable to building mass in other forms than water in containers if suitable mass equivalents are used such as diurnal heat capacities (2).

Heat transfer between the sunspace and the adjoining building is by air circulation only. Three different cases are studied. First, circulation is assumed to be by natural convection through vent pairs whose centers are vertically separated by 8 ft; the combined vent area is varied from 0 to 5% of the projected area. Unless otherwise noted, the vent area is fixed at 5% of the projected area, while other parameters are varied. Second, circulation is assumed to be by a combination of natural convection and fan-forced flow; the fan is switched on and off with a thermostat in the sunspace, the fan thermostat setting being varied from 60 to 100°F, and the fan capacity being varied from 0 to 5 ft^3/min per ft^2 of projected area (cfm/ft^2). Unless otherwise noted, the fan thermostat setting and fan capacity are fixed at 80°F and 3 cfm/ft^2, respectively, while other parameters are varied. Simultaneously, the vent area is varied from 0 to 3% of the projected area, the power requirement of the fan is ignored. Third, the circulation is assumed to be by fan-forced flow alone. The fan parameters are varied as described above for this case also.

Each case is studied with and without movable insulation on the sunspace glazing at night. When used, the movable insulation has a thermal resistance of R-5 and is in place from 5:30 p.m. to 7:30 a.m. solar time.

The building temperature is controlled within the range 65-75°F by the application of auxiliary heating and cooling as needed. There is no incidental internal heat generation. Except for the various means of transferring heat from the sunspace to the building, there is no space conditioning in the sunspace. No auxiliary heat limits the sunspace minimum temperature and no ventilation or other cooling system limits its maximum temperature. The calculations were performed without sunspace temperature limits, even though such limits would be imposed in practice, to determine the unmodified effect of other design parameters on the temperature limits.

2.2. The Method

The performance of the sunspace/building system was computed hour by hour using a general numerical model of a sunspace (3) and the typical meteorological year (TMY) for Boston (4). The calculation was repeated for a set of values of both the heat storage and distribution parameters using the model and TMY mentioned above.

3. THE RESULTS

Each set of results is presented in two ways to characterize both the performance of the sunspace as a solar heater for the adjoining building and the winter sunspace environment for living or growing space. The average annual solar heating performance is expressed by the solar savings fraction, a relative measure of the auxiliary heat eduction in the adjoining building achieved by the sunspace. The winter sunspace environment is expressed by the January temperature extremes, the maximum and minimum temperatures that occurred in the sunspace during the TMY January. Because the maximum temperature was calculated assuming no ventilation, extremely high temperatures are reached in some cases. These high temperatures would not be permitted in practice: thus, the maximum temperature should be regarded as a qualitative indication of the effect of the parameter in question, not as a realistic estimate of the actual maximum.

The results are organized according to the three types of convection heat transfer between the sunspace and the adjoining building: the first is natural convection through vent pairs, the second is a combination of natural convection and fan-forced air flow, and the third is fan-forced air flow alone.

3.1. Natural Convection

The following results apply to the case of heat transfer by natural convection alone. See Section 2.1 for specific assumptions.

A. Vent Area. Figures 2(a) and (b) show the effect of vent area on sunspace performance. The vent area is expressed as a percentage of the projected area. Remember that the vents are assumed to be in pairs with the upper vent 8 ft above the lower vent. The vent area refers to the combined area of both vents. The results are applicable to other vent arrangements provided the vent area is multiplied by a suitable conversion factor to make the area effectively equivalent to the area of an 8-ft vent pair. The most common vent is probably an open door. Multiply the area of a 6-ft 8-in. door by 0.64. Multipliers for other vent configurations are in Ref. (5), pp. 112-113.

Figure 2(a) shows that solar heating performance increases very rapidly with increasing vent area up to about 1% of the projected area. This reflects the fact that air circulation is the only important means of transferring heat through an insulated common wall. For vent areas greater than about 1%, the solar heating performance increases much more slowly as the vent area increases. This effect occurs because these vent areas are capable of a heat flow rate that approaches the limit of the useful heat available from the sunspace.

The curves in Fig. 2(a) are plotted for three values of the building heat capacity (CPMRM): 0, 30, and 60 Btu/°F ft^2 of projected area. Increased building heat capacity has a favorable effect on solar heating performance for all values of the vent area, but the effect is greater the larger the vent area. This relationship can be expressed by stating that there is a limit to the useful vent area that depends on the building heat capacity. For buildings with a small heat capacity, the limit for the case represented by Fig. 2(a) is about 3%: that is, for vent areas greater than about 3%, the solar heating performance is very insensitive to vent area. For buildings with a large heat capacity, the limit to the useful vent area is larger. This is because the large rate of heat flow through large vents tends to produce less

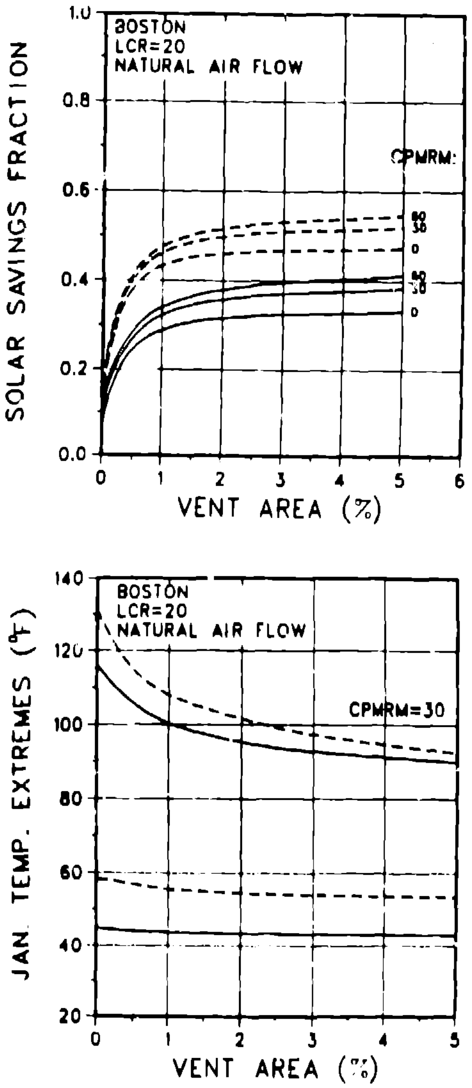

Fig. 2. (a) Annual solar savings fraction and (b) January temperature extremes in the sunspace vs vent area in the common wall as a percentage of the projected area. The parameter CPMRM is the heat capacity in the adjacent building in the unit Btu/°F ft^2 of projected area. The dashed curves are for R-5 night insulation. The solid curves represent no night insulation.

overheating and is, therefore, more useful if the building has a large heat capacity. The limit of useful vent area also depends on the climate and especially on the load collector ratio (LCR). Thus, the particular results presented here should not be applied in general. Curves similar to Fig. 2(a) for low-heat-capacity buildings are in Ref. (5) for six different cities with two values of LCR for each city.

Figure 2(b) shows that the maximum sunspace temperature decreases sharply as the vent area increases up to about 1% of the projected area: it continues to decrease for larger areas. It is also noteworthy that the minimum sunspace temperature is only slightly dependent on the vent area. Thus, in both solar heating and temperature limits, sunspace performance increases with vent area, rapidly at first and then more slowly.

B. Sunspace Mass. Figures 3(a) and (b) show the effect of sunspace heat capacity, or sunspace mass, on sunspace performance. The mass is expressed in the unit Btu/°F ft^2 of projected area. Remember that the sunspace always has a 6-in.-thick concrete floor slab; sunspace mass in Figs. 3(a) and (b) means heat capacity added in the form of water in containers. Figure 3(a) shows that solar heating performance generally increases as sunspace mass increases, with one exception.

The curves in Fig. 3(a) are plotted for three values of the CPMRM: 0, 30, and 60 Btu/°F ft^2 of projected area. All but one show the same tendency of an increase in the solar heating performance as the sunspace mass increases. The exception is for CPMRM = 60 and no night insulation (solid curves). In this case the performance is very insensitive to the sunspace mass. Furthermore, the trend of the curves suggests that there may be an even larger value of CPMRM for which the solar heating performance decreases with added sunspace mass. This is indeed the case as discussed further in the next section, Room Mass.

Figure 3(b) shows that the sunspace temperature extremes are moderated by sunspace mass: the maximum sunspace temperature decreases and the minimum sunspace temperature increases with increased sunspace mass. This is the expected result, and the same trend should apply to all climates and LCRs.

C. Room Mass. Figures 4(a)-(c) show the effect of building heat capacity, or room mass, on sunspace performance. The mass is expressed in the unit Btu/°F ft^2 of projected area. Remember that the room mass is assumed to be in the form of water in containers, but the results are applicable to other forms of room mass such as building materials and furniture, provided suitable equivalent masses are used such as the diurnal heat capacities (2).

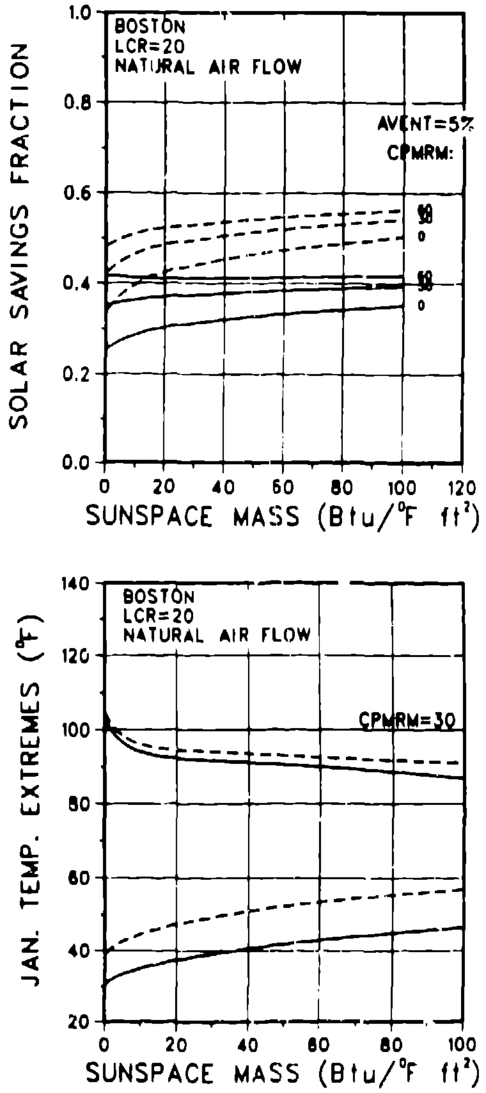

Fig. 3. (a) Annual solar savings fraction and (b) January temperature extremes in the sunspace vs sunspace mass, or added heat capacity, per ft^2 of projected area. The parameter CPMRM is the heat capacity in the adjoining building in the unit Btu/°F ft^2 of projected area. The dashed curves are for R-5 night insulation. The solid curves represent no night insulation.

The curves in Figs. 4(a) and (b) are plotted for three values of the sunspace heat capacity (CPMD): 0, 30, and 60 Btu/°F ft^2 of projected area; and three values of the vent area (AVENT): 2, 3, and 5% of the projected area. They show that the solar heating performance increases as room mass increases for all of the cases studied. This is the expected result. Furthermore, we see that the effect of added room mass is

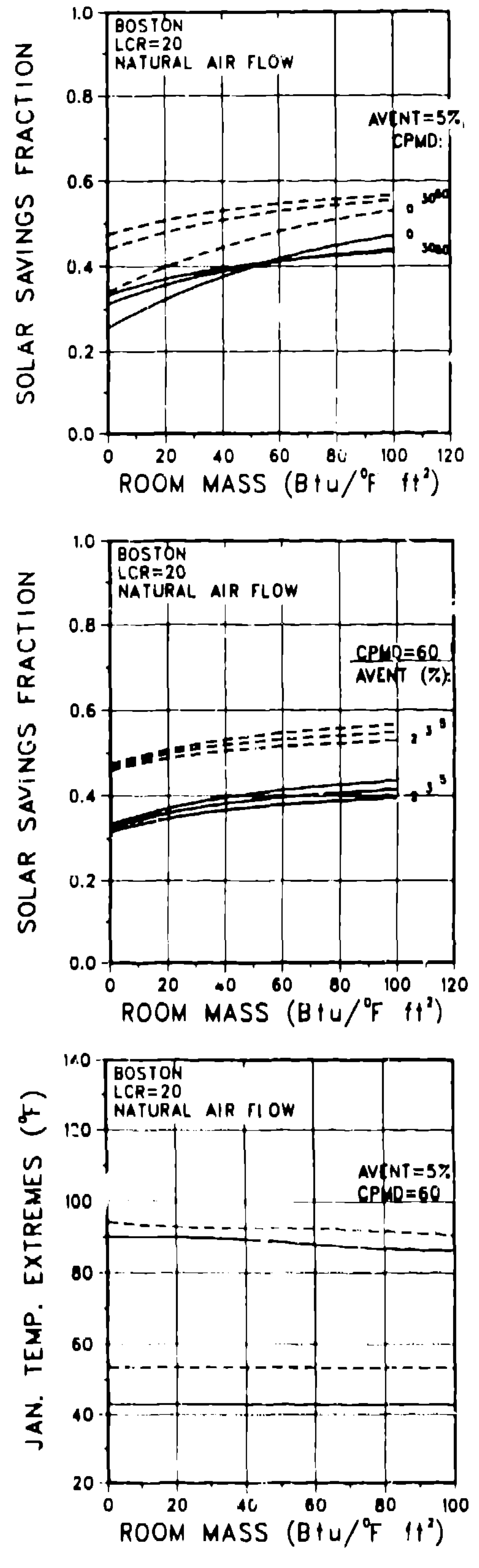

Fig. 4. (a) and (b) Annual solar savings fraction and (c) January temperature extremes in the sunspace vs the room mass, or the heat capacity in the adjoining building, per ft^2 of projected area. The parameter CPMD is the added heat capacity in the sunspace in the unit Btu/^oF ft^2 of projected area. The parameter AVENT is the vent area in the common wall as a percentage of the projected area. The dashed curves are for R-5 night insulation. The solid curves represent no night insulation.

greatest when the sunspace heat capacity is small and the vent area is large.

The most interesting observation from Fig. 4(a) is that without night insulation and for a room mass of about 55 Btu/^oF ft^2 or more, the solar heating performance of a sunspace with a large heat capacity falls below the performance of one with a small heat capacity. However, the performance does not appear to decline any further for a sunspace heat capacity greater than about 30 Btu/^oF ft^2. Thus, if it is desirable to add a sunspace heat capacity of at least 30 Btu/^oF ft^2 to achieve a certain level of temperature stability, despite the solar heating performance compromise that this may entail, it may be desirable to add more than 30 Btu/^oF ft^2 because no further heating performance penalty occurs, but the added mass continues to moderate the temperature extremes. See Fig. 3(b).

Figure 4(c) shows that the minimum sunspace temperature is very insensitive to the room mass. For the case shown here of a relatively large sunspace heat capacity, the maximum sunspace temperature shows only a slight tendency to decline with added room mass. The maximum sunspace temperature can be expected to be more sensitive to the room mass for small sunspace heat capacities.

3.2. Natural Convection and Fan-Forced Convection Combined

The following results are for the case of heat transfer by a combination of natural convection and fan-forced convection. See Sec. 2.1 for specific assumptions. The purpose of this portion of the results is to evaluate the effect of a fan as a supplement to natural convection.

Figures 5(a) and (b) show the effect of fan capacity on sunspace performance. The fan capacity is expressed in the unit ft^3/min ft^2 of projected area (cfm/ft^2).

The curves in Fig. 5(a) are plotted for three values of the vent area (AVENT): 1, 2, and 3% of the projected area. The curves show that the solar heating performance has very little dependence on the fan capacity even for very small vent areas. This means

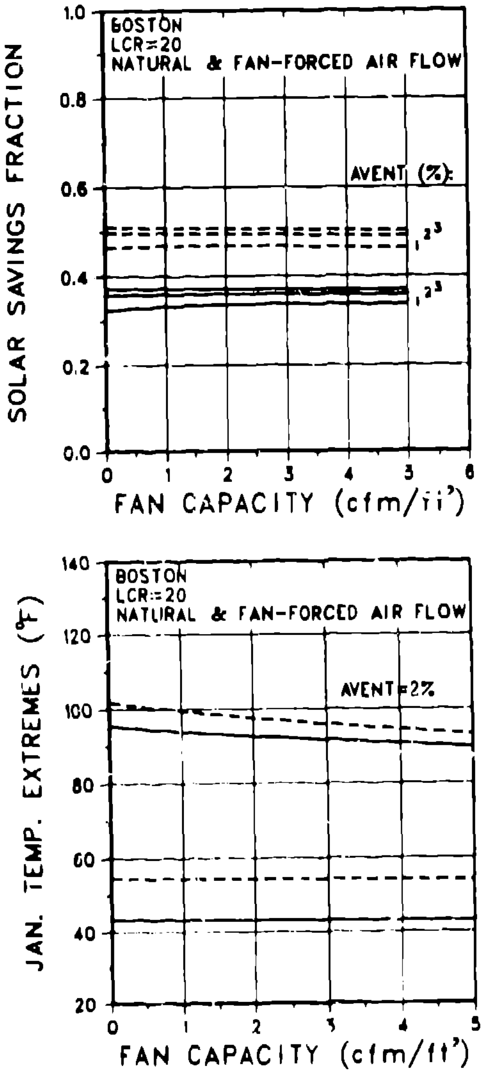

Fig. 5. (a) Annual solar savings fraction and (b) January temperature extremes in the sunspace vs the fan capacity in the unit ft^3/min/ft^2 of projected area (cfm/ft^2) for the case of natural and fan-forced convection combined. The parameter AVENT is the vent area in the common wall as a percentage of the projected area. The dashed curves are for R-5 night insulation. The solid curves represent no night insulation.

that a fan, as a supplement to natural convection, is not capable of significantly improving the solar heating performance for the particular assumptions that apply. The assumptions that may be particularly pertinent are a relatively small LCR (20 Btu/°F day ft^2) and a relatively large sunspace heat capacity (60 Btu/°F ft^2 in addition to the floor slab).

Figure 5(b) shows that the maximum sunspace temperature is affected by the fan capacity even though the solar heating performance is not so affected. Note that the maximum sunspace temperature slowly approaches the fan thermostat setting of 80°F as the fan capacity increases. Nevertheless, it appears that a fan of much larger capacity than 5 cfm/ft^2 would be required to limit the sunspace temperature very closely to the thermostat setting.

3.3. Fan-Forced Convection

The following results are for the case of heat transfer by fan-forced convection alone. See Sec. 2.1 for specific assumptions.

A. Fan Capacity. Figures 6(a)-(c) show the effect of fan capacity on sunspace performance. The fan capacity is expressed in the unit ft^3/min ft^2 of projected area (cfm/ft^2).

The curves in Figs. 6(a) and (b) are plotted for three values of the fan thermostat setting (TFAN): 70, 80, and 90°F; and three values of the building heat capacity (CPMRM): 0, 30, and 60 Btu/°F ft^2 of projected area. We see that the solar heating performance is very sensitive to the fan capacity in the range roughly 0-2 cfm/ft^2. This is because the fan-forced air flow is the only significant form of heat transfer through the insulated common wall. The solar heating performance is relatively insensitive to the fan capacity greater than about 2 cfm/ft^2, although for very lightweight buildings (represented by the curves for CPMRM = 0 Btu/°F ft^2) the performance falls slightly above about 2 cfm/ft^2. This is because above 2 cfm/ft^2 the fan delivers more heat to the building than can be immediately used, and if the building has little heat capacity, the excess heat is wasted. Remember that these results apply to fixed values of the added sunspace heat capacity (60 Btu/°F ft^2), LCR (20 Btu/°F day ft^2), and other design parameters. We expect the optimum fan capacity to be sensitive to these parameters; therefore, the information in Figs. 6(a) and (b) should not be generalized.

Figure 6(c) shows that the maximum sunspace temperature is very sensitive to the fan capacity, particularly in the range 0-2 cfm/ft^2. Note that the maximum sunspace temperature slowly approaches the fan thermostat setting of 80°F as the fan capacity increases. Nevertheless, it appears that a much larger capacity than 5 cfm/ft^2 would be required to limit the sunspace temperature very closely to the thermostat setting. The minimum sunspace temperature is very insensitive to the fan capacity.

It is interesting to compare Figs. 6(a) and (b) with 2(a) and Fig. 6(c) with 2(b). The comparisons show how similar are the roles of the vent area in the natural convection case to the fan capacity in the fan-forced

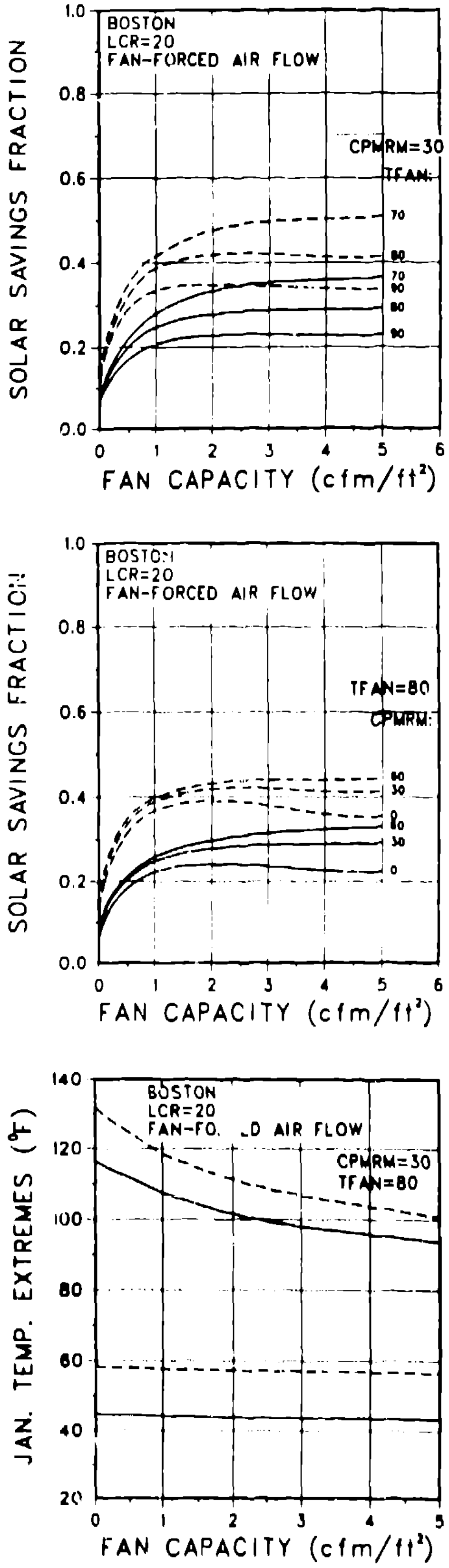

Fig. 6. (a) and (b) Annual solar savings fraction and (c) January temperature extremes in the sunspace vs the fan capacity in the unit ft^3/min/ft^2 of projected area (cfm/ft^2) for the case of fan-forced convection only. The parameter TFAN is the fan thermostat setting in $^\circ$F. The parameter CPMRM is the heat capacity in the adjoining building in the unit Btu/$^\circ$F ft^2 of projected area. The dashed curves are for R-5 night insulation. The solid curves represent no night insulation.

convection case. The dependence of the solar heating performance on the vent area and fan capacity are very similar, with the performance rising rapidly at first and then leveling off. One noteworthy difference is that the solar heating performance rises to a higher level in the natural convection case. This occurs because natural convection air flow depends on the temperature difference between the two spaces and is, therefore, more responsive to the availability of heat in the sunspace. The comparison, however, uses the very simple fan control strategy adopted for this study, namely, a single control temperature in the sunspace and a fixed fan capacity. Presumably, a more elaborate strategy, based on both the sunspace and building temperatures and on a variable-volume fan, could be made to mimic natural convection closely enough to produce comparable performance. There are also advantages of a fan-based system related to the flexibility of control and distribution. Disadvantages include cost, power consumption, noise, and potential breakdowns.

B. Fan Thermostat Setting. Figures 7(a) and (b) show the effect of the fan thermostat setting (setpoint) on sunspace performance.

The curves in Fig. 7(a) are plotted for three values of the fan capacity (CFM): 1, 3, and 5 ft^3/min ft^2 of projected area (cfm/ft^2). We see that the solar heating performance is maximized at a fan setpoint of about 65-70°F, that is, near or slightly above the building auxiliary heat setpoint of 65°F. It is customary, however, to use a slightly higher setpoint to reduce the fan running time and possible discomfort of a cool air stream. We use 80°F in those studies where the setpoint is fixed.

Figure 7(b) shows that there is very little sensitivity of the sunspace temperature extremes to the fan setpoint. This is interesting because we might expect that the maximum sunspace temperature could be controlled through the fan setpoint. This is true, however, only for a sufficiently large fan capacity. Fig. 7(b) was plotted for a fan capacity of 3 cfm/ft^2.

C. Sunspace Mass. Figures 8(a) and (b) show the effect of sunspace heat capacity, or

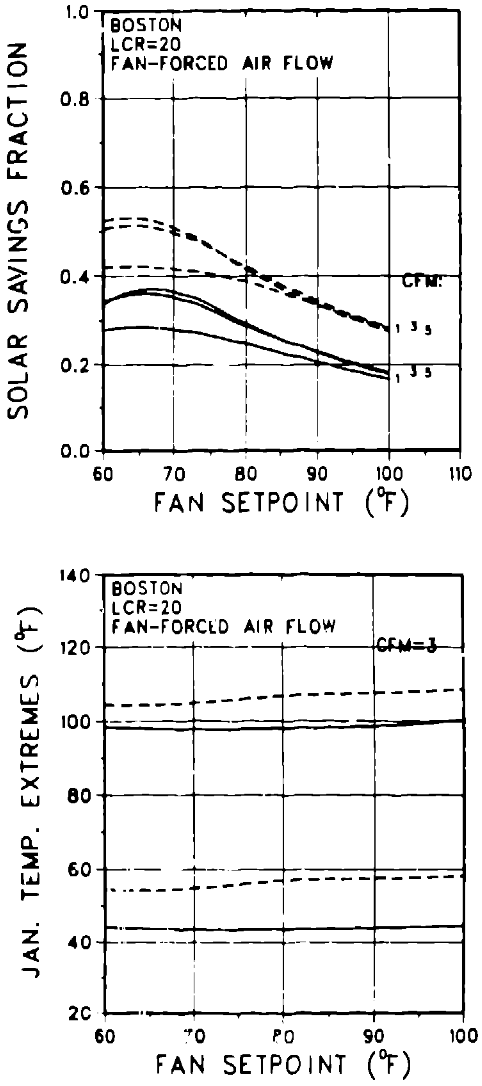

Fig. 7. (a) Annual solar savings fraction and (b) January temperature extremes in the sunspace vs the fan setpoint, or fan thermostat setting, in °F. The parameter CFM is the fan capacity in the unit ft^3/min/ft^2 of projected area (cfm/ft^2). The dashed curves are for R-5 night insulation. The solid curves represent no night insulation.

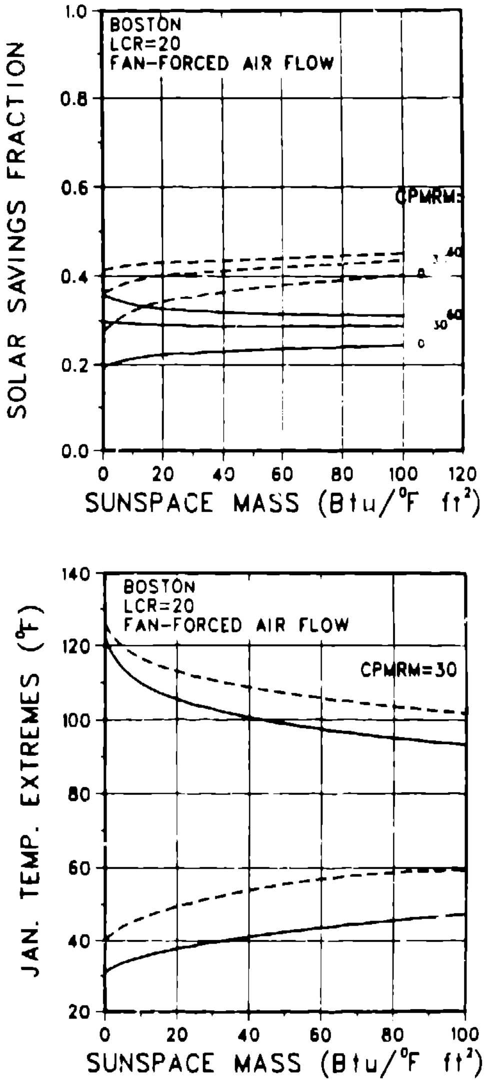

Fig. 8. (a) Annual solar savings fraction and (b) January temperature extremes in the sunspace vs the sunspace mass, or added heat capacity, per ft^2 of projected area. The parameter CPMRM is the heat capacity in the adjoining building in the unit Btu/°F ft^2 of projected area. The dashed curves are for R-5 night insulation. The solid curves represent no night insulation.

sunspace mass, on sunspace performance. The mass is expressed in the unit Btu/°F ft^2 of projected area. Remember that the sunspace always has a 6-in.-thick concrete floor slab; again, sunspace mass in Figs. 8(a) and (b) means heat capacity added in the form of water in containers.

The curves in Fig 8(a) are plotted for three values of the building heat capacity (CPMRM): 0, 30, and 60 Btu/°F ft^2 of projected area. They show that added sunspace mass always improves the solar heating performance in the night-insulated cases, but the effect of sunspace mass in non-night-insulated cases depends on the building heat capacity. Added sunspace mass improves the solar heating performance if the building has a small heat capacity, but added sunspace mass may affect the solar heating performance only slightly or actually reduce it for a larger building heat capacity. This point is discussed further in the next section, Room Mass.

It is interesting to compare Fig. 8(a) with Fig. 3(a). Two features of the comparison are noteworthy. First, added sunspace mass increases the solar heating performance more in the natural convection case, Fig. 3(a), than in the fan-forced case, Fig. 8(a). Second, the solar heating performance is greater in the natural convection case than in the fan-forced case for all levels of sunspace mass. Thus, fan-forced convection compares more favorably with natural convection in the case of a lightweight sunspace than in the case of a massive one, but natural convection still outperforms fan-forced convection in all of the cases studied.

Figure 8(b) shows that the sunspace temperature extremes are moderated by sunspace mass: the maximum sunspace temperature decreases and the minimum sunspace temperature increases with increased sunspace mass. This is the expected result. It is similar to that of Fig. 3(b) for the case of natural convection air flow except that the maximum sunspace temperature is now even more sensitive to the sunspace mass. This extra sensitivity occurs because fan-forced convection is less effective than natural convection at limiting the maximum sunspace temperature, at least for the fan system assumptions made here, so that the sunspace mass is more critical in limiting the maximum temperature.

D. Room Mass. Figures 9(a)-(c) show the effect of building heat capacity, or room mass, on sunspace performance. The mass is expressed in the unit Btu/°F ft^2 of projected area. Remember that the room mass is assumed to be in the form of water in containers, but the results are applicable to other forms of room mass such as building materials and furniture, provided suitable equivalent masses are used such as the diurnal heat capacities (2).

The curves in Figs. 9(a) and (b) are plotted for three values of the sunspace heat capacity (CPMD): 0, 30, and 60 Btu/°F ft^2 of projected area: and three values of the fan capacity (CFM): 2, 3, and 5 ft^3/min ft^2 of projected area (cfm/ft^2). The curves show that the solar heating performance increases as room mass increases for all of the cases studied. This is the expected result. Furthermore, we see that the effect of room mass is greatest when the sunspace heat capacity is small and the fan capacity is large.

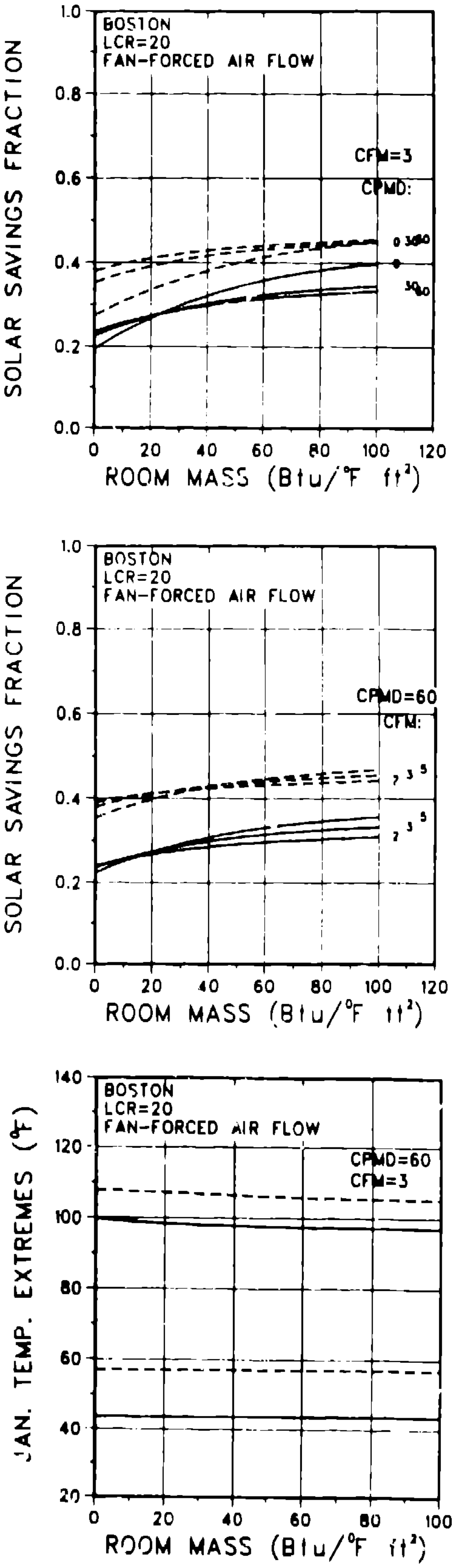

Fig. 9. (a) and (b) Annual solar savings fraction and (c) January temperature extremes in the sunspace vs the room mass, or the heat capacity in the adjoining building, per ft^2 of projected area. The parameter CPMD is the added heat capacity in the sunspace in the unit Btu/°F ft^2 of projected area. The parameter CFM is the fan capacity in the unit ft^3/min/ft^2 of projected area (cfm/ft^2). The dashed curves are for R-5 night insulation. The solid curves represent no night insulation.

The most interesting observation from Fig. 9(a) is that without night insulation and for a room mass of about 25 Btu/°F ft^2 or more, the solar heating performance of a sunspace with a large heat capacity falls below one with a small heat capacity. However, the performance does not appear to decline much further for a sunspace heat capacity greater than about 30 Btu/°F ft^2. Thus, if it is desirable to add a sunspace heat capacity of at least 30 Btu/°F ft^2 to achieve a certain level of temperature stability, despite the solar heating performance compromise that this may entail, it may be desirable to add more than 30 Btu/°F ft^2 because little further heat performance penalty occurs, but the added mass continues to moderate the temperature extremes. See Fig. 8(b).

4. CONCLUSIONS

The above results are based on specific sunspace and building assumptions. Of particular importance are the Boston location and the LCR of 20 Btu/°F day ft^2. Thus, the results should be applied very cautiously to other circumstances. Nevertheless, some generalizations are probably valid.

Added thermal storage mass in the sunspace always improves the temperature stability in the sunspace. Added mass also increases the performance of the sunspace as an air heater for an adjoining building if the sunspace glazing is insulated at night or if the building contains little thermal storage mass. If the building contains abundant thermal storage mass and the sunspace is non-night insulated, added mass in the sunspace may have little effect on or even reduce solar heating performance.

Added thermal storage mass in the adjoining building improves the temperature stability in the building but has little effect on the temperature stability in the sunspace. Added mass in the building always increases the performance of the sunspace as an air heater for that building.

Natural convection is a very effective means to move warm air from the sunspace to an adjoining building. It is more effective than a simple constant-volume fan operated by a thermostat in the sunspace set at 80°F. The comparison applies to both the solar heating performance of the sunspace and the limitation of the maximum sunspace temperature. This conclusion does not address the possible advantage of a fan in distributing heat to remote spaces or a fan with a more elaborate control strategy.

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