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EFFECT OF RADIATION, WIND VELOCITY AND TEMPERATURE DIFFERENTIAL ON NATURAL GAS CONSUMPTION OF GREENHOUSES: PRELIMINARY REPORT

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Editor's Note: **The Colorado State University Climate Control System operates with the metric system of units, and the derivation of the relationships in this article are in metric. With the exception of the figures and formulae, however, the discussion is in English units wherever possible with appropriate conversions.**

TWO SETS OF EQUATIONS, SHOWING THE RELATIONSHIPS BETWEEN GAS CONSUMED AND RADIATION, WIND VELOCITY AND IN-TO-OUTSIDE TEMPERATURE DIFFERENTIAL, WERE CALCULATED FOR TWO GREENHOUSE COVERS WITH AND WITHOUT THERMAL SCREENS. THE NIGHT TIME EQUATIONS WERE LINEAR AS CONTRASTED TO CURVILINEAR FOR THE DAY TIME. UNDER STANDARD CONDITIONS, AT NIGHT A DOUBLE COVER REDUCED GAS CONSUMPTION 40%. A DOUBLE COVER PLUS A THERMAL SCREEN REDUCED ENERGY REQUIRED 55%. AT AN OUTSIDE LIGHT INTENSITY OF ABOUT 5300 FOOT-CANDLES, DOUBLE COVER ALLOWED AN OUTSIDE TEMPERATURE OF 22°F BEFORE HEATING WAS REQUIRED, AS COMPARED TO A SINGLE COVER WHERE AN OUTSIDE TEMPERATURE OF 31°F REQUIRED HEATING AT THE SAME LIGHT INTENSITY.

During the period covered by the rose results presented in CGGA Bulletins 449 and 450, the climate control system recorded total natural gas consumption each time the system switched between night and day settings. All four greenhouses (960 sq. ft. each) were controlled at identical air temperatures of 62°F night and 72°F minimum day. The treatments consisted of two houses covered with double, air-inflated polyvinyl fluoride (DBL PVF), one house with a combination shade and thermal screen (PVF SHD), and two houses with a single, 5 oz. fiber-reinforced plastic (FRP and FRP SHD). The system recorded outside air temperature, outside wind velocity and outside radiation. Data at the end of day or night were printed as averages for the previous period. In order to obtain hourly data for gas consumption, the total for the period was divided by hours in the period. The same practice was required for total accumulated solar radiation.

For our purposes over 100 days, when the outside temperature was below the inside, were selected, and the data subjected to multiple linear regression analyses in order to derive the mathematical equation which best described gas consumption as a function of the three outside conditions. These results represent a preliminary report. Since these data were obtained, the program software has been changed to allow the operator to record gas consumption at the same time as other climatic variables are recorded at any interval from one to several minutes. Our ultimate objective is to provide suitable algorithms for computer control that will increase greenhouse fuel efficiency.

Night conditions

The lack of any solar radiation during the dark period simplified the corresponding equations so that:

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DBL PVF: $\text{Gas} = 0.955\text{DT} + 0.700\text{WV} - 0.881$, $R^2 = 0.93$,

FRP SINGLE: $\text{Gas} = 1.503\text{DT} + 2.670\text{WV} - 0.170$, $R^2 = 0.94$,

FRP SHD: $\text{Gas} = 1.081\text{DT} + 0.956\text{WV} - 0.286$, $R^2 = 0.83$, and

PVF SHD: $\text{Gas} = 0.701\text{DT} + 0.917\text{WV} - 0.526$, $R^2 = 0.91$,

where: Gas = cubic meters per hour gas consumption (1 cu.m. = 35.3 cu.ft).

DT = temperature difference from inside-to-out in °C (1.0°C = 1.8°F).

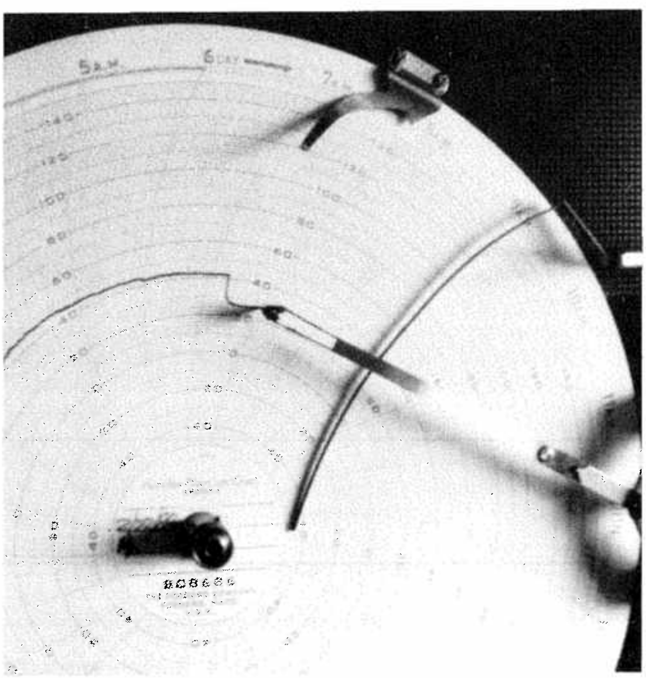
WV = wind velocity in meters per second (1 m/s = 2.2 mph), and

R^2 = the adjusted correlation where 1.00 is perfect.

The results were plotted in **Fig. 1** which depicts the obvious differences between a single layer and its higher infiltration rate, as contrasted to a double, air-inflated cover. Assuming zero wind velocity, the FRP single would require 878 cubic feet of gas per hour to maintain a 62°F inside temperature at freezing outside; in contrast to the DBL PVF requirement of 531 cu.ft. under the same conditions, or a 40% reduction in gas requirement to heat a 960 sq.ft. area (0.9 cu.ft./sq.ft. versus 0.6).

A thermal screen, under the same conditions (30 F DT, O WV) reduced gas consumption 29% under FRP as contrasted to 26% reduction under PVF. The greatest advantage of a thermal screen was under an FRP cover in overcoming the effects of high wind velocities outside. At a wind velocity of 15 mph, the single FRP required 1,516 cu.ft./hr. as compared to 851 cu.ft./hr. for the same cover with a thermal curtain — a 44% saving. Under the same conditions of wind and temperature, a thermal screen under DBL PVF reduced gas consumption by 12%. For some reason, the effect of wind velocity on gas requirement was greater where a thermal screen was employed under DBL PVF. The constants (0.700 versus 0.917) have not been tested to determine if they were significantly different from each other.

Since the equations are linear, some other interesting relationships may be derived. For example, the equation for FRP SINGLE says, essentially, that 1.333 cubic meters of



What makes Colorado interesting — and difficult? A cold front moves through and the temperature drops in less than 15 minutes from 42°F to nearly 24°F. This is when you want a good heating system that comes on *toute suite.* Most people from other climates find this hard to understand, especially when it comes to designing heating systems for greenhouses.

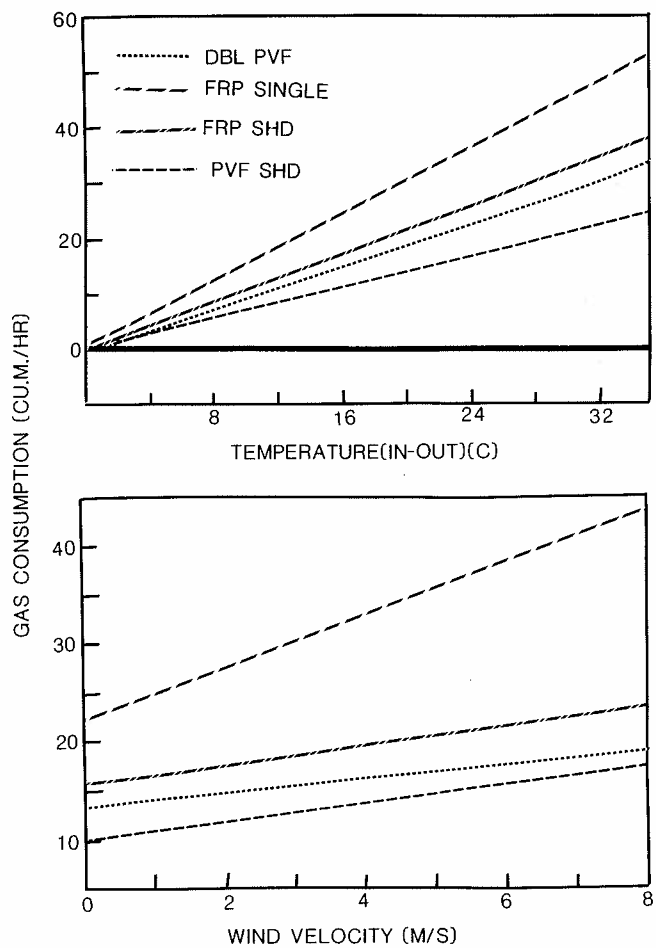


Fig. 1: Natural gas consumption at night for four different combinations of greenhouse cover and thermal screen.
Upper: Effect of temperature difference inside-to-out at a wind speed of 0.5 meters/sec (1.1 mph).
Lower: Effect of wind velocity at a temperature difference of 15°C (27°F).
DBL PVF: double air-inflated polyvinyl fluoride,
FRP SINGLE: single layer 5 oz. fiber-reinforced plastic,
FRP SHD: FRP with a thermal screen, and
PVF SHD: PVF with a thermal screen.
(1.8°F = 1.0°C and 1 cubic meter = 35.3 cubic feet)

gas would be required per hour if the temperature difference from in-to-outside was one degree C and wind velocity zero. The total surface area was about 2,184 sq. ft. (includes insulated north and side walls). At Ft. Collins' altitude (800 BTU/cu.ft. gas), this would translate to 9.6 BTU loss every hour for each square foot of surface area and each degree difference across the material. This value is much larger than the 1.2 BTU hr^{-1} ft^{-2} $°F^{-1}$ usually given in the literature as the transfer coefficient for fiberglass. A part of the difference may be due to high internal wind movement resulting from the fan-jet, forced hot-air heating, the large surface area-to-volume ratio of a small greenhouse, and the quonset-shaped design. With the present data, the transfer coefficient for DBL PVF translated to 0.82 BTU hr^{-1} ft^{-2} $°F^{-1}$ which is about three tenths of a BTU larger than published values (0.5). The equations show, however, considerable variability in the origins (0.881, 0.170, 0.286, and 0.526) which would drastically effect calculation of the transfer coefficient. These relationships, therefore, represent a first approximation and indicate the improvements required for future determinations.

Day conditions

Solar radiation increased complexity of the derived heating formulae. It was necessary to transform gas consumption into natural logarithms in order to perform the statistical analyses:

DBL PVF: $\ln Gas = 0.112DT - 0.0016R + 0.163WV + 0.928$, $R^2 = 0.87$,

FRP SINGLE: $\ln Gas = 0.112DT - 0.0014R + 0.216WV + 1.544$, $R^2 = 0.90$,

FRP SHD: $\ln Gas = 0.122DT - 0.0011R + 0.188WV + 1.134$, $R^2 = 0.89$, and

PVF SHD: $\ln Gas = 0.113DT - 0.0015R + 0.223WV + 0.567$, $R^2 = 0.91$,

where: R = outside radiation in kiloJoules per square meter-hour (100 KJ m^{-2} hr^{-1} = 2.6 watt-hours per sq. ft.), and

lnGas = cubic meters of gas expressed as a natural logarithm.

The shade curtains during the period when these data were considered were seldom closed during the daylight hours. Although one may observe differences between houses with and without screens, we do not think that much credibility can be given to them. In general, however, a screen, even when opened, appeared to reduce natural gas consumption. Of particular interest would be the effect of external sunlight on energy consumption by the structures during the day. For example, at an outside solar radiation level of 2000 KJ/sqm-hr, the equivalent light intensity would be approximately 5300 foot-candles — around noon on a bright clear day in the fall or spring. For a DBL PVF cover, this would be equivalent to 799 cu.ft. of gas per hour at zero wind. The outside temperature would have to be nearly 50°F below the inside 72°F air temperature before the heating system would come on — or, 22°F outside. On the

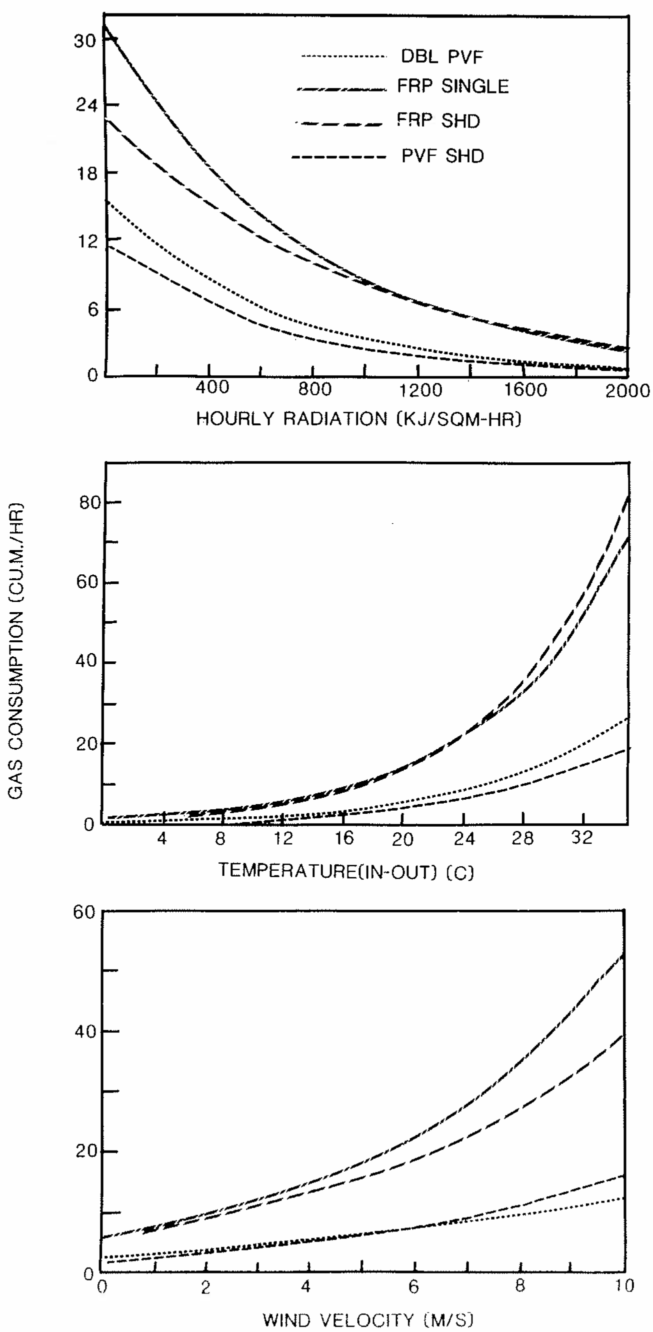


Fig. 2: Natural gas consumption during the day of four different combinations of greenhouse covering and thermal screen.

Upper: The effect of outside solar radiation at a temperature difference of 15°C (27°F) and a windspeed of 1 m/s (2.2 mph). Radiation in kiloJoules per square meter-hour (100 KJ/sqm-hr = 27.8 watt-hours per sq.m. = 2.6 watt-hours per sq.ft.).

Middle: The effect of temperature difference inside-to-out at a radiation level of 1100 KJ/sqm-hr (about 3000 foot-candles sunlight intensity) and a windspeed of 1 m/s (2.2 mph).

Lower: The effect of windspeed at a temperature difference of 15°C (27°F) and a solar radiation level of 1100 KJ/sqm-hr (about 3000 ft-c).

(1 cubic meter = 35.3 cubic feet)
(1 meter/second = 2.2 mph)
(1°C = 1.8°F)

other hand, the same radiation level under FRP SINGLE would be worth about 475 cu.ft. or a temperature difference from in-to-outside of around 40°F — or, near freezing. At 1000 KJ/sqm-hr, however, for the same temperature differences, DBL PVF would require 415 cu.ft./hr as contrasted to 529 cu.ft./hr for FRP SINGLE to maintain 72°F. From the standpoint of energy conservation, a tight, double covered greenhouse offers considerable advantage regardless of day or night period, even though total radiation transfer is significantly reduced by a double cover. On the other hand, opportunities for CO_2 injection would be greater with the single FRP cover, since the house would be less likely to ventilate at a given radiation and outside temperature compared to a double cover.

Equations of this type can constitute so-called "transfer" functions, if incorporated into computer software. With appropriate feedback, an error signal can be generated which controls the greenhouse climate for maximum growth, commensurate with maximum fuel efficiency. There is no reason why an appropriate plant model cannot be included. We think research of this type offers one of the more significant advances in greenhouse technology in the near future.

FORT COLLINS GREENHOUSE CLIMATOLOGICAL SUMMARY FOR FOUR WEEKS, BEGINNING JANUARY 31, 1988

(See Bulletin 426 for details.)

	Week beginning							
	Jan. 31		Feb. 7		Feb. 14		Feb. 21	
	Day	Night	Day	Night	Day	Night	Day	Night
Average outside temperature (°F)	23	17	41	29	41	31	44	34
Maximum outside temperature (°F)	52	44	58	48	60	48	62	55
Minimum outside temperature (°F)	9	4	22	10	24	17	21	17
Degree-days of heating	294	336	168	252	168	238	147	217
Accumulated total solar radiation (MJ/sq.m.)	54	1	50	0	80	1	91	1
Average relative humidity (%)	71	80	46	68	40	60	43	59
Maximum relative humidity (%)	94	99	99	98	90	89	85	91
Minimum relative humidity (%)	17	32	12	18	21	29	8	10
Average absolute vapor pressure (mb)	3	3	4	4	3	3	4	3
Average wind speed (mph)	2	1	5	2	7	4	2	2
Maximum wind speed (mph)	17	12	49	20	26	56	29	28
Average CO_2 concentration (Pascal)	37	0	36	0	36	0	37	0
Maximum CO_2 concentration (Pascal)	42	0	50	0	49	0	54	0
Accumulated gas consumption (cu.ft./sq.ft.)	69	149	37	82	53	111	34	91

Editor's Note: This is the last weekly summary to be given in the CGGA Bulletin.

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