# 연료 자동조절 버너를 갖춘 빈 시스템에서의 벼 건조에 관한 시뮬레이션

# Simulation of Rice Drying in a Bin System with an Automatic Gas-Modulating Burner

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## 적 요

곡물 빈에서 벼 건조시 외기 온도에 따른 연료 자동 조절 및 배출공기의 재순환이 에너지 소비, 건조비용 및 건조 시간에 미치는 효과를 분석하기 위해 슬램II(SLAM II : Simulation Language for Alternative Modeing II)를 이용한 시뮬레이션 모델을 개발하였다. 따라서 약 64톤의 벼를 연료 자동조절 버너를 갖춘 곡물빈에서 열풍 건조할 때, 절약 가능한 에너지 양과 공기 재순환의 효과를 시뮬레이션을 통해 분석하였으며 이를 실제의 자료와 비교하여 이 모델을 검증하였다.

시뮬레이션에 의한 본 연구의 결과는 다음과 같다.

1. 배출공기를 재순환 시키지 않는 상태에서 자동 연료조절 버너를 사용할 경우 관행 버너를 이용한 빈 시스템에 비해, 루이지애나 주에서 8월에 25%의 에너지를 절약할 수 있으며 12월에는 8%의 에너지를 절약할 수 있다. 실제의 건조 실험에서는 8월에 약 30%의 에너지를 절감할 수 있었다.
2. 자동 연료조절 버너를 갖춘 빈 시스템에서 제습을 하지 않은 배출 공기의 재순환은 건조 에너지 소비량과 건조 시간을 증가시켰으며 연료 자동조절 장치의 에너지 절약 효과를 감소시켰다. 따라서 배출공기를 재순환하여 에너지를 절감하고자 할 때에는 반드시 배출 공기를 제습시켜 습도를 재조절 해야만 했다. 또한 제습된 공기의 재순환 효과는 여름보다 겨울에 더 컸다.
3. 연료 자동조절 버너를 갖춘 빈 시스템에서 벼를 건조할 경우 루이지애나 주, 8월에 물벼의 톤당 건조비용은 $2.13 이었으며 관행 버너를 갖춘 시스템에서는 $2.69이었다. 실험에 의한 실제 건조비용은 자동화 시스템에서 $2.17이었고 관행 시스템에서는 $2.62이었다.

## INTRODUCTION

Grain drying is a common and necessary processing operation among farmers in an effort to maximize crop income. Large amounts of energy are used for rice drying on Louisiana farms. Louisiana produces about 15% (Johnson and Linscombe, 1988) of the U. S. rice crop, and a third of the rice farmers in the state use in-bin farm drying. This drying accounts for 7.7% of the total energy required for rice production in Louisiana(Rutger and Grant, 1979). Rice drying in Louisiana is controlled by two main factors : the high ambient relative humidity during the

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rice drying season and an upper limit of 38℃ air temperature for rice drying to produce good milling yields. Rice is more susceptible to damage during subsequent handling and processing operations than other grains if it is dried at temperatures much above 38℃.

The weather conditions in rice growing areas vary, and to preserve the milling quality it is also critical not to overheat the rice grain during drying. Determining the energy required in drying rice and developing ways to save energy input could benefit rice farmers and the industry. Traditional drying with gas or other fossil-fuel heat sources requires an optimum control system to modulate the fuel amout based on the ambient air conditions, the input heat rise at the heater, the moisture content, rice depth, and airflow being used. A technique using exhaust air from a dryer can also be useful to conserve energy and to prevent overdrying of the rice. Thermostatic controls are available that modulate the gas flow according to the conditions of the air after the mixing of ambient air and recirculated air with or without dehumidification.

The ratio of the recirculated air to the mixed air, by volume, influences the fuel saving and drying rate of rough rice. The conditions of exhaust air leaving the drier and ambient air are a function of grain conditions, ambient conditions, dryer parameters, and hence the drying time. So the drying potential of the mixed air, which is heated, varies, with drying time, air recirculation ratio, and dehumidification of recirculated air. If the amount of fuel used in heating the air is modulated by a thermostatic valve to heat the mixed air to an optimum drying temperature of 38℃, considerable fossil-fuel can be saved, and uniform rough rice drying can be achieved with minimum damage to quality.

Hence, a computer simulation was required for investigating the effects of such a gas-modulating control system with air recirculation. Such a simulation can predict the fuel amount required during each drying time step and the total fuel saved in a gas-modulating control system for in-bin rice drying. Also, it was useful to analyze the effect of air recirculation ratio with /without dehumidification of fuel consumption and drying rate in such an in-bin rice drying system with a gas control. A simulation model using SLAM II (Pritsker, 1986) was developed to analyze such a drying system.

### OBJECTIVES

The specific objectives of this study were :

1. To simulate the effect of gas-modulating control based on ambient air conditions on gas and electric energy consumption and drying cost in on-farm bin rice systems,
2. To simulate the effects of air recirculation and dehumidifcation of the recirculated air on the energy consumption, drying cost, and drying time for rough rice,
3. To estimate the energy an the drying-cost savings of the gas-modulating control system compared with an in-bin rice drying system with a conventional burner.

## SIMULATION ASSUMPTIONS AND PROCEDURES

### Assumptions of Simulation

The following assumptions were for keeping the simulation simple :

1. Rice drying process was adiabatic with no conduction losses.
2. A sensible heat equation was used to calculated the energy required to heat the drying(mixed) air during each time step. The sensible heat surrendered by the air in passing through the grain is equal to the latent heat of vaporiza-

tion required to vaporize the water from the grain.

3. All the parameters of the sensible heat equation were assumed to be functions of time.

4. Natural gas was used as a fuel for heating the air during rice drying. The heat of combustion of the natural gas was assumed to be 49.395 MJ/kg or 33.625 MJ/m$^3$.

5. The efficiency of the burner, which starts burning automatically if any gas exists, was assumed to be 0.95 based on the actual drying data (Verma and Jacobsen, 1987), and the burning rate of gas released from a tank was also assumed to be constant.

6. The amount of fuel required in heating the mixed air was assumed to be modulated accurately by a thermostatic valve to heat the air to an optimum drying temperature of 38℃.

7. Temperature and relative humidity of ambient air were assumed to be sinusoidal functions of time. Extreme values of their functions were assumed to be obtained at 3 P.M.

8. The capacity of an air fan(Model CCD-270-15 XL, 11.2 kW) was assumed to be 360 cmm.

9. A physical dehumidifier was, if required, used to reduce the humidity of recirculated air to the condition of ambient air. Its energy consumption was assumed to be zero because the dehumidifier made of a physical filter can remove the moisture of recirculated air using the solar energy of a greenhouse.

10. Initial conditions of rice drying of one batch were as follows :

a) Total weight of wet rough rice was W=63, 625(kg). b) Initial moisture content of the sample was $M_o$= 0.307(decimal, d.b.), and final moisture content was $M_f$=0.126(decimal, d.b.). c) The static pressure drop of air was indicated by HEAD=0.116(m of water). d) Rice drying started at 9 A.M. and was conducted continuously for a of rice in August and December in southwest Louisiana. e) Drying efficiency of the bin dryer with a diameter of 8.23m was 0.8.

## Simulation Procedures

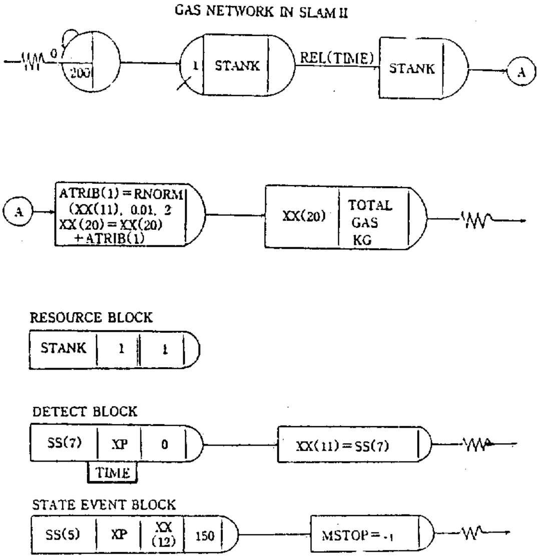
### A. Network of Drying System

SLAM II/PC was used to simulated the drying system as it has been demonstrated to analyze process models with both continuous and discrete events. The drying system described in this study had events that occurred at different time steps, determined as the gas in the burner tank was run out. The amount of gas required in heating the mixed air(ambient air plus exhaust air) to an optimum drying temperature of 38℃ during each time step was released from a gas storage tank or a line to a burner tank as an entity, XX(11), of a network. The amount of a released entity was determined according to ambient and recirculated air conditions that change with time.

For simplification, the ambient air conditions were expressed as functions of time. The accumulated amount of heat, SS(2), a state variable of SLAM II, required during rice drying period was then simulated by analyzing psychrometric properties of the mixed air, which also change according to the air recirculation ratio.

The network of fuel used for rice drying is shown in figure 1. The gas stored in a storage tank waited in an AWAIT node until the emptiness of the burner tank was detected by a DETECT node, and the amount of gas required during next time step was determined.

After the amount of gas was released to the burner tank in a normal distribution by a thermostatic valve of the storage tank, the gas amount was assigned by an ASSIGN node to ATRIB(1), an attribute variable of SLAM II. Then the gas amount of each time step and total amount used for rice drying were collected and plotted by a COLLECT node and a RECORD



- STANK : storage tank of gas.
- SS(5) : total removed water
- SS(7) : gas required during each time step
- XX(12) : total water to be removed from grains

**Fig 1. SLAM II network in a gas modulating control system of rice drying.**

statement. The gas released from the storage tank was burned in the burner at a constant rate, which was expressed as a TERMINATED node.

Finally, the simulation time was also determined by calculating the water removing rate during each time step, accumulated removed water, and total water to be removed from the grain. When the accumulated removed water, SS(5), reached the total water, XX(12), to be removed from the grain, the current time, TNOW, became a total simulation or drying time for a batch of rice. The drying time was detected by a STATE EVENT node, and the simulation program was stopped at time of TNOW.

B. Ambient Air Conditions

Functions representing ambient air conditions were developed based on the weather data observed at Lake Charles and the LSU Rice Research Station at Crowley, Louisiana. The hourly mean temperature and relative humidity observed at 3-hour intervals during August and September in 1982 and 1983 were plotted in figures 2 and 3. The mean weather data in December from 1940 to 1985 in South Louisiana were also used(Ruffner and Bair, 1987). The hourly mean temperature and relative humidity were expressed as sinusoidal functions. The mean maximum temperature and relative humidity and mean minimum temperature and relative humidity were used to determine amplitudes of the sinusoidal functions. The data observed at 9 A. M. were used as initial conditions of the sinusoidal functions, and the extreme values of temperature and relative humidity during a day were assumed to be observed at 3 P.

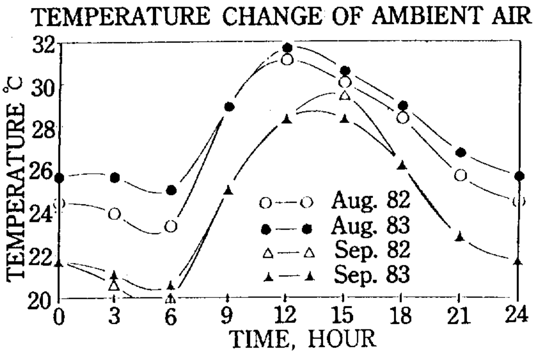


Fig 2 Mean hourly ambient air temperature in South Louisiana (August and September).

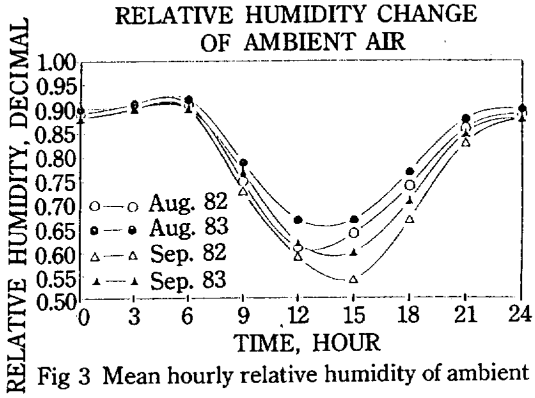


Fig 3 Mean hourly relative humidity of ambient air in South Louisiana (August and September).

M. The developed functions are as follows, and their $R^2$ values were greater than 0.7(significant at a 1% level, SAS/STAT, 1985) :

$T(t)=28.6+5.4\times \sin(PI\times time/12)$

in Aug. of '82, '83, '86

$T(t)=11.44+5.56\times \sin(PI\times time/12)$

in Dec. of '40 to '85

$RH(t)=0.778-0.138\times \sin(PI\times time/12)$

in Aug. of '82 and '83

$RH(t)=0.77-0.13\times \sin(PI\times time/12)$

in Dec. of '40 to '85

Where, t=time(hour), PI=3.14

T=ambient air temperature(℃)

RH=ambient air relative humidity(decimal).

C. Heat Required During Each Time Step

The energy required to heat the mixed air (ambient air plus recirculated air) during each time step was calculated from the following sensible heat ($q_1$) equation(Brooker et al., 1982) : $q_1=Ca\times 60\times V/v_a\times (T_{38}\text{-}Tmix)\times (DTNOW\ /\ 1000$

where, $q_1$=heat required during each time step (DTNOW), MJ

Ca =heat capacity of air, KJ/(kg°K)

=4.18 [0.24+H{597.3 / (T+273)+0.441}]

V =airflow rate, 360cmm

$v_a$ =specific volume, $m^3$/kg, dry air

DTNOW =step size of drying time, hour

$T_{38}$ =optimum drying temperature, 38℃

Tmix =temperature of mixed air, ℃

The variables, Ca, $v_a$, and Tmix, were respectively calculated by the following procedures :

1) First, an exhaust air temperature, T=SS(3), was calculated at time=t. The exhaust air temperature varies from a point 'c' to 'b' as shown in figure 4, which could be expressed as an exponential function of drying time :

$dT/dt=-XK\times(T-38)$, or $SS(3)=38+(Tc-38)\times \exp(-XK\times t)$

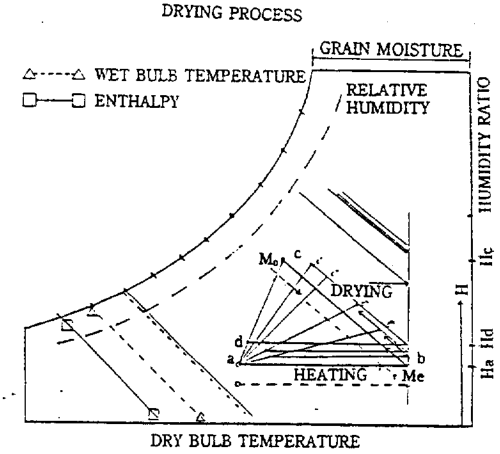


**Fig 4 Representation on the psychrometric chart of the process of rice drying with air recirculation.**

where, an initial value of SS(3), Tc, and a constant, XK, were obtained from an actual drying test.

2) The absolute humidity, Hc(t)=SS(4), at time=t could be also expressed as an exponential function of drying time :

$dH/dt=-XK\,(H-Ha)$

or $SS(4)=XX(6)+\{Hc-XX(6)\}\times \exp(-XK\times t)$

where, an initial value of SS(4), Hc, was obtained from a drying test and Ha was absolute humidity of ambient air, XX(6).

3) The temperature of mixed air, Td(point 'd'), Td=XX(4), was expressed by $Td=Ta(t)+XX(2)\times\{T-Ta(t)\}$.

where, Ta=ambient air temperature(℃)=XX(3), in August

$=28.6+5.4\times \sin(PI\times TNOW/12)$

XX(2) =ratio of recirculated air to mixed air in volume, decimal.

Therefore, $XX(4)=XX(3)+XX(2)\times\{SS(3)-XX(3)\}$.

4) The absolute humidity, Hd(t)=XX(7), of mixet air was calculated using the relative

humidith of ambient air, $RHa(t)=XX(5)$, similar to that of the tenperature of mixed air. The absolute humidity of ambient air was expressed by the following equation(Brooker et al., 1982) :

$$Ha(t)=XX(6)=0.6219\times RHa(t)\times SVP/\{ATM+RHa(t)\times SVP\}$$

where, ATM=atmospheric pressure(101.325 kPa)

SVP =saturated vapor pressure of the air(KPa)$=f(Ta(t))$

$$RHa(t)=0.778-0.138\times \sin(PI\times TNOW/12)=XX(5)\text{, in August.}$$

Therefore, the absolute humidity (kg/kg) of mixed air, XX(7), was

$$Hd=Ha(t)+XX(2)\times\{Hc-Ha(t)\}$$

or $XX(7)=XX(6)+XX(2)\times\{SS(4)-XX(6)\}$

However, if a dehumidifier was used to remove the water in the exhaust air to bring it to condition of the ambient air, the term $\{SS(4)-XX(6)\}$ was assumed to be zero.

5) The specific volume of mixed air ($m^3/kg$), $v_a=XX(8)$, was $XX(8)=2.833E-3\times\{XX(3)+273\}\times\{1+1.6078\times XX(7)\}$ (Brooker et al., 1982).

6) The heat capacity (kJ/kg°K), $Ca=XX(9)$, of mixed air was calculated by the following equation : $XX(9)=4.18\times[0.24+Hd(t)\times\{597.3/(Td(t)+273)+0.441\}]=4.18\times[0.24+XX(7)\times\{597.3/XX(4)+273)+0.441\}\}$

7) The mixed air was assumed to be delivered from a fan to the heater. Then, the amount of heat, XX(10), supplied by the fan was considered as auxiliary heat. The horsepower of the fan was calculated as follows :

$$HP=V\times r\times HEAD/4500=360/XX(8)\times HEAD\times 835.2/4500$$

where, HP=horsepower of the air fan, hp

V =airflow rate delivered, 360 cmm

r =specific weight of mixed air$=1/va=1/XX(8)$, $kg/m^3$

HEAD =static pressure drop, m of water

The static pressure drop in m of water should be converted into air height ; 1 m of water=835.2 m of air. The efficiency of the electrical fan was assumed to be 0.7, so the actual power was 0.7×HP. The accumulated heat(MJ), SS(6), supplied by the fan was expressed as follows :

$$SS(6)=SSL(6)+360/XX(8)\times 835.2/4500\times 2.845\times DTNOW$$
$$=SSL(6)+179.367552\ /\ XX(8)\times HEAD\times DTNOW$$

Where, SS(6)=accumulated heat supplied by the fan to the mixed air,

SSL(6)=immediated past value of SS(6) at time TNOW-DTNOW

1 hp=2.6845 MJ., DTNOW=time step

Therefore, a temperature increment, XX(10), due to the energy supplied by the fan during each time step was calculated as follows :

Heat required to raise temperature by DT during each time step$=Ca\times 60\times V\ /\ v_a\times DT\times DTNOW$ or $179.3672/XX(8)\times HEAD\times DTNOW\times 1000\times 0.7=Ca\times 60\times 360\times /v_a\times DT\times DTNOW$

Therefore, $DT=179.3672/XX(8)\times HEAD\times 1000\times 0.7/XX(9)/60/360\times XX(8)$
$=5.812825926\times HEAD\ /\ XX(9)=XX(10)$

Consequently, the energy(MJ), $q_1=XX(1)$, required to heat the mixed air to a temperature of 38℃ during each time step could be calculated by the following equation :

$$XX(1)=XX(9)/XX(8)\times 60\times 360\times\{38-XX(4)-XX(10)\}\times DTNOW/0.95$$

where 0.95 indicates the thermal efficiency of the burner.

The amount of gas (kg), SS(1), required for the heat energy during each time step was XX(1)/49.395, where 49.395 MJ/kg indicates the heat of combustion of natural gas. The total amount of gas consumed in the burner was also calculated as follows :

SS(1) = SSL(1) + XX(1) / 49.395, where SSL(1)was an immediated past value of SS(1). The amount of gas to be released into the burner tank during each time step was expressed as follows : SS(7) = XX(1) − GASMIN

where GASMIN was aninitial small amount of gas in the burner. Hence, when the amount of gas, SS(7), crossed a threshold of zero, the gas required for the next time step was released from a storage tank or line to the burner tank, which was detected by a DETECT node. The total amount of gas released, XX(20), was computed by a COLLECT node until the drying was completed.

### D. Simulation Time rol System

The water removal rate during each time step and the accumulated removed water were calculated to determine the simulation time(total drying time). The water removal rate(WMR) was the product of input mass airflow rate and the difference between absolute humidity of exhausted air at time=t and absolute humidity of mixed air, and it can be expressed as : WMR = {60×V / XX(8)} × {SS(4) − XX(7)}.

The water removed during each time step was WMR×DTNOW, and the accumulated removed water, SS(5), was expressed by the following equation using SLAM II variables :

SS(5) = SSL(5) + 60×360 / XX(8) × {SS(4) − XX(7)} × DTNOW.

Then, total water, XX(12), to be removed from an initial moisture content($M_o$, decimal, dry basis) of the grain(W, kg) to a final moisture content($M_f$, decimal, dry basis) was W× ($M_o - M_f$). Consequently, when the accumulated removed water reached the total water to be removed for rice drying, the current time, TNOW, was considered as the total drying simulation time.

Finally, the controlled drying system with air recirculation and with or without dehumidification, and the conventional drying system were compared in terms of energy consumption of gas and electricity, drying time, enetgy savings, and drying costs. The effects of gas modulating control and air recirculation were analyzed. The simulation model was validated by comparing the simulation results with actual data obtained in the in-bin drying tests conducted by Verma and Jacobsen (1987).

## RESULTS AND DISCUSSION

### Effects of Gas-Modulating and Air Recirculation

The in-bin drying system with a conventional burner consumed gas and electricity at the rates of 3.396 and 0.288 MJ/kg of water removed, respectively, during drying, whereas the system with a gas-modulating burner consumed gas of 2.589 MJ/kg of water removed and electricity of 0.230 MJ/kg of water removed in the simulation of the rice drying system based on the August weather data in southwest Louisiana. The gas energy consumption values obtained in this simulation were very similar to the actual data of Verma and Jacobsen(1987), which were 3.34 MJ/kg of water removed in the conventional system and 2.496 MJ/kg of water removed in the gas-modulating control system, respectively. About 82% of total energy in the control system was used in heating the ambient air to 38℃. A savings of approximately 25% of the total energy required in drying was achieved in the simulation.

The appoximate drying time in the conventional system estimated by using the mean water removal rate was 141.8 hours, whereas the simulated drying time in the modulating control system estimated from the varying water remo-

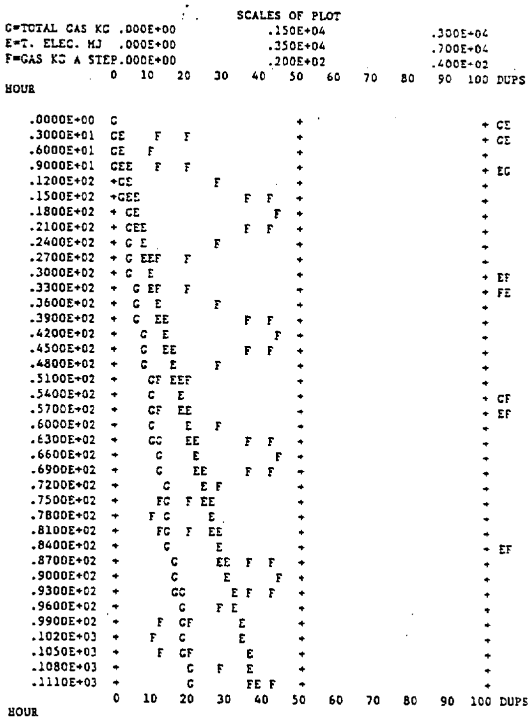


Fig 5 Plot of accumulated energy consumption in electricity and gas and of gas amount consumed during each time step in the gas control system without air recirculation in August.

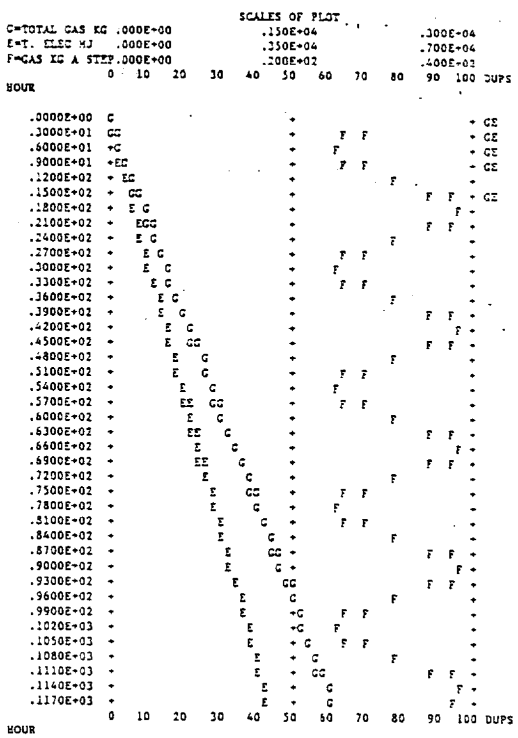


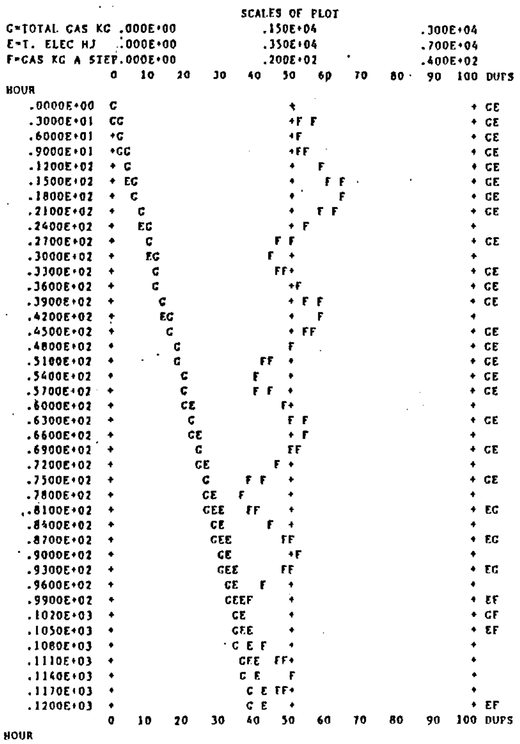
Fig 6 Plot of energy consumption in electricity and gas in the gas control system without air recirculation in December.

val rate for each time step was 112 hours. The actual drying time (Verma and Jacobsen, 1987) in the control system varied between 110 hours and 130 hours.

The amount of gas required during each time step varied like a sinusoidal function of ambient air temperature as shown in figures 5−7. The gas amount decreased during the daytime and increased during the nighttime, as expected. The electrical energy to power the fan was used in proportion to the total drying time.

The gas-modulating control system with air recirculation of 10 percent and without dehumidification used gas and electric energy at the rates of 2.905 and 0.250 MJ/kg of water removed, respectively. The energy savings in the gas modulating control system decreased from 25% to 15%, and the drying time increased from 112 hours to 122 hours. In the control system with air recirculation of 20% and 30%, the energy consumption of gas also increased to 3.358 and 3.885 MJ/kg of water removed, respectively, and their energy savings were changed to 1.14% and −15.54%, respectively, compared with the conventional system.

The effect of air recirculation to conserve drying energy was adverse because the water removal rate decreased due to the high humidity of the recirculated air. Consequently, the recirculated air always required dehumidification to conserve the energy of exhaust air. However, as the ambient air temperature in August was relatively high compared with other months in southwest Louisiana, air recirculation with de-



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                                   SCALES OF PLOT
G=TOTAL GAS KG .000E+00             .150E+04                  .300E+04
E=T. ELEC MJ   .000E+00             .350E+04                  .700E+04
F=GAS KG A STEP.000E+00             .200E+02                  .400E+02
               0    10   20   30   40   50   60   70   80   90   100 DUPS
HOUR
    .0000E+00  C                        +                        + CE
    .3000E+01  CC                       +F F                     + CE
    .6000E+01  +C                       +F                       + CE
    .9000E+01  +CC                      +FF                      + CE
    .1200E+02  + C                      +   F                    + CE
    .1500E+02  + EC                     +    F F                 + CE
    .1800E+02  +  C                     +      F                 + CE
    .2100E+02  +   C                    +   F F                  + CE
    .2400E+02  +   EC                   + F                      +
    .2700E+02  +    C                 F F                        + CE
    .3000E+02  +    EC               F  +                        +
    .3300E+02  +     C                FF+                        + CE
    .3600E+02  +     C                  +F                       + CE
    .3900E+02  +      C                 + F F                    + CE
    .4200E+02  +      EC                +   F                    +
    .4500E+02  +       C                + FF                     + CE
    .4800E+02  +        C               F                        + CE
    .5100E+02  +        C           FF  +                        + CE
    .5400E+02  +         C         F    +                        + CE
    .5700E+02  +         C         F F  +                        + CE
    .6000E+02  +         CE             F+                       +
    .6300E+02  +          C             F F                      + CE
    .6600E+02  +          CE            + F                      +
    .6900E+02  +           C            FF                       + CE
    .7200E+02  +           CE        F  +                        +
    .7500E+02  +            C     F F   +                        + CE
    .7800E+02  +            CE   F      +                        +
    .8100E+02  +            CEE   FF    +                        + EC
    .8400E+02  +             CE      F  +                        +
    .8700E+02  +             CEE       FF                        + EC
    .9000E+02  +              CE        +F                       +
    .9300E+02  +              CEE      FF                        + EC
    .9600E+02  +               CE   F   +                        +
    .9900E+02  +               CEEF     +                        + EF
    .1020E+03  +                CE      +                        + CF
    .1050E+03  +                CEE     +                        + EF
    .1080E+03  +                C E F   +                        +
    .1110E+03  +                 CEE  FF+                        +
    .1140E+03  +                 C E    F                        +
    .1170E+03  +                  C E FF+                        +
    .1200E+03  +                  C E   +                        + EF
               0    10   20   30   40   50   60   70   80   90   100 DUPS
HOUR
```

Fig 7 Plot of energy consumption in the control system with dehumidified air recirculation of 50% in December.

humidification was not required.

The conventional and controlled systems required more than twice as much drying energy in December as in August. The energy consumption rates of the conventional and control systems without air recirculation were 8.276, 7.631 MJ/kg of water removed in gas, and 0.266 and 0.253 MJ/kg of water removed in electricity, respectively. The energy saved was only 7.72% compared with the total energy of the control system without air recirculation. The effect of the gas-modulating control on the energy saved significantly decreased in December compared with that of the gas control in August. The control system with 10% air recirculation and without dehumidification in December also showed similar trends in energy requirement to that of the control system in August. Air recirculation without dehumidification required more energy because it extended the rice drying time, and the energy saving of the gas modulating control system was −6.75% with the drying time being extended by 22 hours.

The control system with dehumidified air recirculation required less energy than the conventional system as the air recirculation ratio increased. The control system with 10% air recirculation and dehumidification saved 12.9% of the energy and extended the drying time by two hours. As the ratio of dehumidified air recirculation to the total mixed air by volume increased from 10% to 80% in steps of 10%, the energy consumption rate in gas decreased significantly as shown in figure 8. Hence, the energy savings in rice drying for one batch increased by 12.9, 18.6, 25.8, 31.8, 38.9, 44.7, 50.9, and 57.3%, respectively. Furthermore, the amount of gas required during each time step gradually decreased with drying time, forming a sinusoidal curve. This trend was more obvious at a higher ratio of dehumidified air recirculation.

Consequently, the gas-modulating control system with dehumidified air recirculation could save a significant amount of drying energy com-

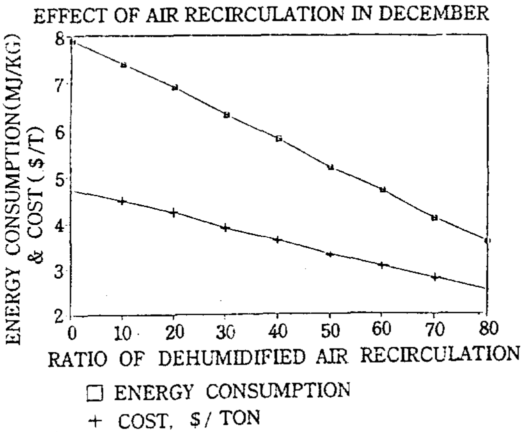

Fig 8 Energy consumption rate and drying cost in the gas-modulating control system with dehumidified air recirculation.

pared with the conventional system when no energy consumption of the dehumidifier was assumed. However, if an electrical dehumidifier was used for recirculated air instead of a solar energy dehumidifier, the optimum ratio of dehumidified air recirculation would be determined based on the energy consumption of the dehumidifier.

## Drying Cost

A. Cost of In-Bin Rice Drying in August

In drying a ton of rough rice from 22% (w.b.) to 13.5% (w.b.), 98.3kg of water must be removed. At an energy consumption rate of 3.67 MJ /kg of water removed in the drying system with a conventional burner, it requires 360.76 MJ (351.91 MJ) of energy, whereas at 2.82 MJ/kg (2.86MJ/kg) of water removed in the gas control system without air recirculation, it requires 277.21 MJ(281.14 MJ). The values in parentheses indicate the average data from actual drying tests of Verma and Jacobsen(1987).

As 91% (90%) of the total energy is from gas and 9% (10%) from electricity as a result of this simulation; therefore, each ton of grain requires 7.30kg(7.12 kg) of gas and 9.02 KWh(8.80KWh) of electricity in the conventional system, and 5.61kg(5.69kg) of gas and 7.70KWh(7.81KWh) of electricity in the gas-modulating control system without air recirculation.

Considering gas at $0.27/kg and electricity at $0.08 per KWh, the cost of gas is $ 1.97($ 1.92) and electricity is $ 0.72($0.70) in the conventional system, whereas in the gas control system the cost of gas is $ 1.51($ 1.54) and electricity is $0.62($0.63). Therefore, the total cost per ton of wet rice is $2.13($2.17) in the gas control system without air recirculation. The control system with air recirculation and without dehumidification did not reduce the drying cost because of the increase in total drying time.

B. Cost of In-Bin Rice Drying in December

The cost of electricity in drying a ton of rough rice in December is similar to that in August, but the cost of gas in December increases by more than double compared with that in August. The costs of gas and electricity per of wet rice are $4.45 and $0.67, respectively, with a total cost of $5.12 for the conventional system. Gas and electricity costs in the control system without air recirculation are $4.10 and $0.63, respectively, with a total cost of $4.73.

The gas-modulating control system with air recirculation and dehumidification could significantly reduce the drying cost if the cost of the humidifier is ignored. In the control system with dehumidified air recirculation of 10% to 80 %, the total costs per ton ton of wet rice are $4. 50, $4.25, $3.91, $3.64,%$3.32, $3.06, $2.79, and $2.51, respectively. Hence, rice drying with a gas-modulating control system in December requires dehumidification of recirculated air to save drying energy.

## CONCLUSIONS

1. The gas-modulating control system without air recirculation saved 25% energy in Augst and 8% in December of the total rice drying energy. Compared with the conventional system in the simulation based on the weather data in southwest Louisiana, the energy saving in the actual drying test in August was about 30%.

2. The energy consumption rates of gas and electricity in the modulating control system without air recirculation were 2.59(2.50) MJ/kg and 0.23(0.30) MJ/kg in August and 7.63 and 0. 23 MJ/kg in December, respectively. Those in the conventional system were 3.40(3.34) MJ/kg and 0.29(0.36) MJ/kg in August and 8.28 MJ/kg

and 0.27 MJ/kg in December, respectively. The values in parentheses indicate the actual data.

3. Air recirculation without dehumidification increased the drying energy consumption and drying time in both August and December, and it decreased the energy savings of the gas-modulating.

4. The modulating control system with dehumidified air recirculation reduced drying energy by 12.9%, 18.6%, 25.8%, 31.8%, 38.9%, 44.7%, 50.9% and 57.3% in December as the recirculation ratio increased from 10% to 80% in steps of 10% under an assumption of no energy consumption by the dehumidifier.

5. The total drying cost in August per ton of wet rice was $2.69($2.62) for the conventional system and it was $2.13($2.17) for the gas-modulating control system without air recirculation. Air recirculation was not required in August because of the high drying potential of ambient air in south Louisiana.

6. The total drying cost per ton of wet rice in December was $5.12 in the conventional system and $4.73 in the gas control system without air recirculation.

7. The gas-modulating control system with dehumidified air recirculation saved drying cost. As the dehumidified air recirculation ratio increased form 10% to 80% in steps of 10%, the total cost per ton of wet rice decreased gradually from $4.50, $4.25, $3.91, $3.64, $3.32, $3.06, $2.79, to $2.51 respectively.

## REFERENCES

ASAE, Data, 1979, Agricultural Engineers Yearbook of Standards, St Joseph, MI.

Brooker, D.B., F.W. Bakker-Arkema, and C.W. Hall. 1982. Drying Cereal Grains, The AVI publishing company, Inc. Westpory. Conn.

Chung, J. H. 1989. Modeling, Simulation and Automatic Control for Optimum Drying and Storage of Rough Rice in a Bin System, Unpublished Dissertation, Louisiana State University.

Johnson, L. E. and S. Linscombe. 1988. Out look of Louisiana's Agriculture, Louisiana Cooperative Extention Service, Louisiana State University Agricultrure Center.

Pritsker, A. A. B. 1986. Introduction to Simulation and SLAM II, A Halsted Press Book, John Wiley & Sons, System Publishing Corproation. West Lafayette, Indiana.

Records of river and climatological observations, WS FORM E−15. Crowley and Lake Charles Weather station, Louisiana. U.S. Department of Commerce.

Ruffner, J. A., and F. E. Bair. 1987. Weather of U.S. Cities. 3rd ed. Volume 1. Gale Research Company, Book Tower, Detroit, Michigan.

Rutger, J. N., and W. R. Grant. 1979. Energy use in rice production. Handbook of Energy Utilization in Agriculture, edited by D. Pimental. CRC Press, Inc., Boca Raton, Flolida, P.93∼98.

SAS/STAT Guide for personal Computers. 1985. Version 6 ed. SAS Institute Inc. Cary, North Carolina.

Verma, L. R., and L. A. Jacobsen. 1987. Gas modulating control for in-bin drying ASAE Paper No. 87−6036., ASAE, St. Joseph, Mich.

Wang, C. Y. 1978. Simulation of thin-layer and deep-bed drying of rough rice. Unpublished. Ph. D. Dissertation. University of California, Davis.