*KOREAN J. FOOD SCI. TECHNOL.*
*Vol.* 17, *No.* 1 (1985)

# In-Bin Drying of Paddy with Ambient Air: Influence of Drying Parameters on Drying Time, Energy Requirements and Quality

**Hong-Sik Cheigh, Werner Mühlbauer*, Jong-Whan Rhim****
**and Myung-Gon Shin****

*Pusan National University, Pusan, Korea, *Institut für Agrartechnik,*
*Universität Hohenheim, Stuttgart, Germany,*
***Korea Advanced Institute of Science and Technology, Seoul*

---

# 상온통풍에 의한 벼의 In-Bin 건조 : 건조시간, 에너지 소요량 및 품질에 미치는 건조조건의 영향

**최홍식 · W. 물바우어* · 임종환** · 신명곤****

부산대학교 식품영양학과 · *독일 호헨하임대학교 농업기술 연구소
**한국과학기술원 생물공학부

## Abstract

Low-temperature in-bin paddy drying has been examined to study the limitations of this drying method under Korean weather conditions, the initial moisture content of the paddy, the bulk depth and the airflow rate. The results are reported and discussed with regard to drying time, energy requirements and costs, uniformity in the moisture content of the dried kernels and, finally, the quality of the paddy. The tests carried out during the paddy-drying period in 1981 and 1982 have shown that under Korean weather conditions paddy can be dried to safe storage conditions by continuous aeration with ambient air. Depending upon the initial moisture content of the kernels (19.2%-25.5% w.b.), the bulk depth (1.1-3.5 *m*) and the airflow (3.0-6.9 $m^3$ air/$m^3$ paddy/*min*) the paddy could be dried within 5 to 17 days. The energy requirements and energy costs are shown to be considerably lower than for conventional high-temperature drying. No significant changes in the quality in terms of milling yield, cracking ratio, acid value and germination were observed.

## Introduction

The traditional paddy-drying system in Korea generally consists of two stages. In the first stage the unthreshed paddy is laid out in the field or bound into small bundles and lined up. The paddy is dried by the sun and wind to a moisture content of approximately 18% w.b. After threshing the drying is completed in a second stage by spreading the paddy in thin layers on ricestraw mats or paved areas. The traditional drying methods require a high input of labour and considerable losses of mass have been reported. The natural drying methods also increase the proportion of broken kernels during milling. The development of improved drying methods has become increasingly important, especially after high yielding varieties were introduced to Korea. Shattering losses in the field are one of the characteristics of the high yielding varieties(1).

The introduction of the mechanical rice dryers used in Japan, the United States or other countries causes many problems if they are adopted by Korean farmer. High investment costs and the need for fossil fuels for heating the drying air are the main disadvantages of mechanical dryers and prevent their wide dissemination.(1,2,3) Low-cost small-scale dryers for on-farm use must be urgently developed to solve the present drying problem. In-bin low-temperature drying seems to be one of the most feasible drying methods best-suited to the requirements of the Korean farmers(4). In-bin low-temperature (LT) drying with ambient air offers certain advantages over high-temperature drying because of the low capital investment, minimum management and lower energy costs. The efficiency of LT-drying does, however, depend upon uncontrollable weather conditions.

The technique of low-temperature in-bin drying of grain has been examined in-numerous research works.

Wenner(5), Maltry(6), Ekström(7), Morey(8), Mühlbauer(9) and others have studied low-temperature drying of wheat; Foster(10), Morey(11), Shove(12), Kuppinger(13) and others have investigated low-temperature corn drying. Yet only a few experiments(14-19) on low-temperature paddy drying have been conducted in the past. Fan management strategies for continuous humidistat and time-clock controlled operation were investigated by Morey(20) and Mühlbauer(9). Results are also available for single and delayfill procedures and for mixing grain during drying by using stirring devices(21). The performances achieved with slightly preheated air using electric or fossil fuel sources and also solar energy are compared with systems employing ambient air by pierce(22). Foster(23), Morey(24), Chung(25) and others. And also the influence of different management techniques on the performance obtained by LT drying has also been studied by means of computer simulation(26-30). Previous tests have shown that grain can be dried to safe storage conditions under certain environmental conditions without significant mass losses or changes in quality. The main factors influencing drying time, energy consumption and equipment costs are the moisture content of the harvested kernels, the airflow rate, the bulk depth, the fan, heating and loading management techniques and, finally, the temperature and relative humidity of the ambient air. The airflow rate in particular greatly influences the energy consumption. So it becomes important to determine the minimum airflow which can be expected to dry the grain without a significant loss of dry matter and an unacceptable increase in fungi contamination before the drying is complete. The objective of this paper is to investigate in-bin LT drying of paddy under the Korean climatic conditions by means of full-scale drying tests considering the various parameters described above.

## Materials and Method

### Equipment

Four circular steel bins measuring 3.0*m* in diameter and 5.0*m* in height were constructed for low-temperature in-bin drying tests.(4) The capacity of each bin is 20 tons of paddy rice when filled to a bulk depth of 4.0 *m*. The bins were fitted with a perforated floor 0.5 *m* from the bottom. Centrifugal fans driven by electric motors of 0.75 *kW* and 2.5 *kW* respectively were attached to each bin. A bucket elevator, distributors and screw conveyors were installed for automatic loading and unloading.

### Instruments

The instruments were fitted to ensure continuous measurement of the temperature and relative humidity of ambient, drying and exhaust air as well as the grain temperature at different bulk depths and different diameters of the bin. The temperatures were measured with thermocouples and the dewpoint temperature with lithiumchloride sensors. The data were registered with multipoint recorders at one-minute intervals. A portable electric thermometer and copper-constantan thermocouples were used to monitor the grain temperature at various points in the bulk. An inlet nozzle was used to determine the airflow rate by measuring the difference in pressure as a result of the constriction, employing a manometer. The atmospheric pressure drop of air through the grain was measured with an $H_2O$ manometer. All the pressures were measured at daily intervals. Wattmeters were used to record the fans' electric consumption. A double concentric tube-type trier was employed to obtain samples of paddy for quality evaluations and for determining the moisture content at various points in the bulk. Fig. 1 shows one of the experimental bins with the sampling points for moisture content determination and the positions of the sensors.

### Paddy rice

Drying experiments were conducted with paddy harvested in 1981 and 1982. The variety chosen was a medium-grain rice variety IR 342 grown in the Suewon area. Using a combine harvester the paddy was harvested with moisture contents ranging from 19.2% to 25.5% w.b. After pre-cleaning, the paddy was transported to KAIST and loaded directly into the bins using a bucket elevator and distributors.

### Procedure

In the 1981 drying tests Bins 1 and 2 were loaded with paddy to a depth of 1.1 *m* and Bins 3 and 4 to a depth of 1.6 *m*, equivalent to 5.0 and 7.5 tons respectively. After being loaded, the paddy was ventilated continuously—except on rainy days—until the moisture content in the upper layer was reduced to around 16% w.b.. During the drying period the airflow was kept at 5 $m^3$ air/$m^3$ paddy/min in Bins 1 and 2 and at 6.9 $m^3$ air/$m^3$

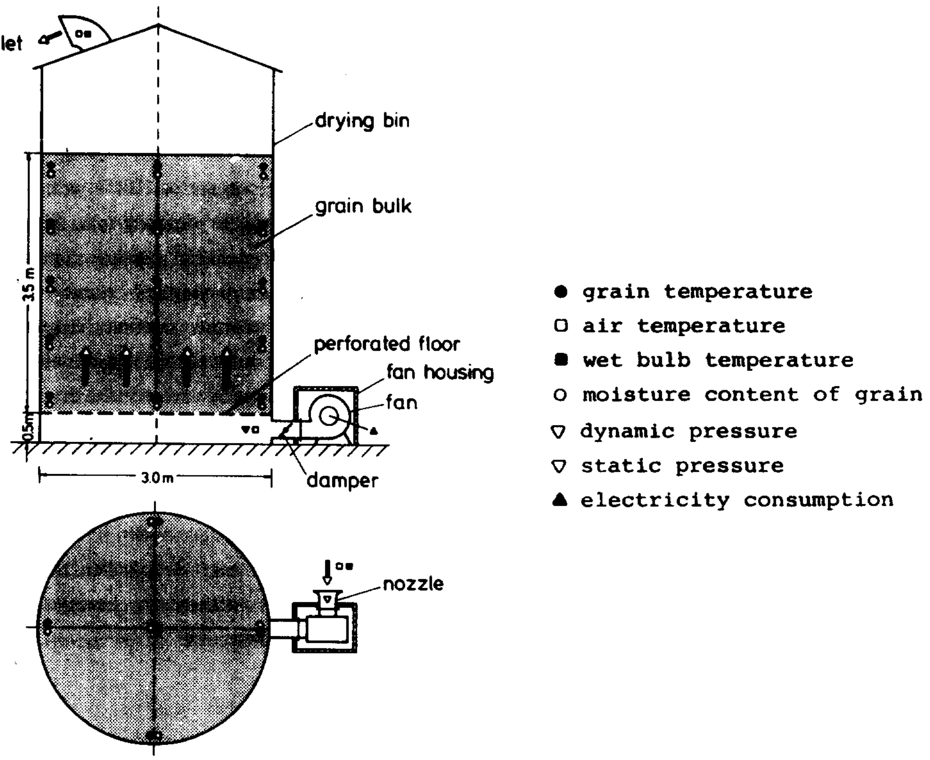

**Fig. 1. Schematic diagram of an experimental bin with sampling points for moisture content determination and the positions of the sensors**

paddy/ min in Bins 3 and 4 based on the results of previous studies.(4,19) In 1982 the airflow was reduced to 3 $m^3$ air/$m^3$ paddy/min. Bin 1 was loaded to a depth of 1.75 *m* and Bin 2 to 3.5 *m*, equivalent to approximately 8.0 and 16.0 tons, respectively. The water removed during the drying process was determined by weighing the wet and dried grain of each bin. The average initial and final moisture content of the paddy before loading and after drying was determined by taking samples. Five samples per layer were taken regularly once or twice a day at the positions shown in Fig. 1 to determine the changes in the moisture content of the paddy in relation to its bulk depth and the drying time. The moisture content of the samples was ascertained by the oven method. The grain temperature was also measured at one-day intervals at the positions shown in Fig. 1. To check the influence of low-temperature drying on the quality of the dried paddy samples were taken after drying and the bulk density, dehulling and polishing rate, milling yield, cracking ratio, germination rate and acid value were determined. The dehulling and polishing rate and the milling yield were ascertained by the methods outlined in the Agricultural Product Inspection Manual(31) To determine the milling properties 300 *g* of paddy rice were dehulled in a Satake testing dehuller and 165 *g* of brown rice were milled for 175 seconds in a Satake testing mill. The cracking ratio was ascertained by manual dehulling of 100 kernels. The cracking lines of each kernel were detected with the help of magnifying glasses. Germination rate and acid value were determined by the procedure described in the manuals(31,32).

A control sample (C) of approximately 4 *kg* of paddy was taken from each bin and spread thinly to dry by ambient air in order to compare the influence of low-temperature drying (LTD) and natural drying upon the quality of the dried paddy.

## Results and Discussion

The results of the low-termperature drying tests are summarized in Tables 1 and 2. Fig. 2 and 3 show the temperature,, relative humidity and drying potential of the ambient air during the paddy drying periods in 1981 and 1982. The moisture contents of the paddy in relation to drying time and bulk depth are given in Fig. 4 and 5.

### Weather Conditions

The low-temperature drying tests conducted in 1981 and 1982 have shown that paddy can be dried under the Korean climatic conditions without losses of quality by means of continuous ventilation with ambient air.

Analysis of the meteorological data during the drying periods in 1981 and 1982 shows that the climate in the Seoul area was cool and dry (Fig. 3 and 4). The temperature and relative humidity were 3.0 to 22.0 °C and 32% to 80% with average values of 14.6 °C and 63% during the drying period of 2-14 October 1981. The equivalent figures between 20 September and 13 October 1982 were 8.0 to 28.5 °C and 25% to 96% with average values of 17.8 °C and 65% respectively.

The average quantity of water which can in theory be absorbed by the drying air represents the air's drying potential. The drying potential of the ambient air depends upon the temperature and relative humidity and must be determined by iterative procedures. The calculated drying potential during the paddy-drying season ranged from 0.00156 to 0.00168 *kg* of water per *kg* of air in 1981 and from 0.00173 to 0.00178 in 1982 (Table 1). These figures indicate the high drying potential of the ambient air during the paddy-drying season in the Seoul area. Under these favourable conditions the ambient air can be used for low-temperature paddy-drying without pre-heating. This causes a significant reduction in the capital costs of the low-temperature drying systems since no electric heater is required.

**Drying Time**

As Table 1 indicates, it takes approximately 5 days to dry a layer of 1.1 *m* to safe storage condition from an initial moisture content of 19.4% w.b. using an airflow rate of 5.0 $m^3$ air/$m^3$ of paddy/min. Nine days were required to dry from initial moisture content of 24.6% w.b. A slightly higher drying rate occurs when paddy with higher initial moisture contents is dried. An increase from 1.1 to 1.6 *m* of the bulk depth and from 5.0 to 6.9 $m^3$ air per $m^3$ of paddy extends the drying time only from 5 to 6.2 days and from 9.2 to 9.8 days. Some attempts were made in 1982 to improve the efficiency of the low-temperature drying system by reducing the airflow rate and increasing the bulk depth. Those tests have shown that even an extremely deep bulk of 3.5 *m* could be dried in about 17 days without any changes in quality by applying an airflow rate of 3.0 $m^3$ air/$m^3$ paddy/*min*.

**Energy Requirement**

The fans installed for the low-temperature drying tests were larger than necessary. This allowed a wide range of variations in the airflow rate but also caused the fans to operate at different efficiencies, depending upon the airflow rate and the pressure drop in the bulk. The

**Table 1. Summary of the results of the 1981 and 1982 low temperature in-bin drying tests**

| | | 1981 | | | | 1982 | |
|---|---|---|---|---|---|---|---|
| | | Bin 1 | Bin 2 | Bin 3 | Bin 4 | Bin 1 | Bin 2 |
| Initial moisture content | % w.b. | 19.4 | 24.6 | 19.2 | 25.5 | 25.1 | 21.7 |
| Final moisture content | | | | | | | |
| average | % w.b. | 13.6 | 14.7 | 14.5 | 15.6 | 12.6 | 13.5 |
| minimum | % w.b. | 12.3 | 12.8 | 11.6 | 15.1 | 11.8 | 12.8 |
| maximum | % w.b. | 14.7 | 16.6 | 15.0 | 17.1 | 14.4 | 15.6 |
| Air temperature | | | | | | | |
| average | °C | 13.8 | 14.6 | 13.8 | 15.2 | 17.1 | 17.9 |
| minimum | °C | 3.0 | 3.0 | 3.0 | 8.0 | 8.0 | 8.0 |
| maximum | °C | 21.5 | 22.0 | 21.5 | 22.0 | 28.0 | 28.5 |
| Relative humidity | | | | | | | |
| average | % | 60 | 62 | 60 | 64 | 64 | 64 |
| minimum | % | 32 | 32 | 32 | 41 | 26 | 25 |
| maximum | % | 80 | 80 | 80 | 80 | 96 | 89 |
| Drying potential | kg $H_2O$/kg air | 0.00168 | 0.00163 | 0.00168 | 0.00156 | 0.00173 | 0.00178 |
| Airflow rate | $m^3$air/$m^3$ paddy min | 5.0 | 5.0 | 6.9 | 6.9 | 3.0 | 3.0 |
| Air velocity | m/s | 0.09 | 0.09 | 0.18 | 0.18 | 0.09 | 0.17 |
| Grain depth | m | 1.1 | 1.1 | 1.6 | 1.6 | 1.7 | 3.5 |
| Pressure drop | Pa | 176 | 196 | 637 | 735 | 245 | 823 |
| Mass of wet grain | kg | 5000 | 5000 | 7500 | 7500 | 8000 | 16000 |
| Mass of dried grain | kg | 4709 | 4427 | 7156 | 6594 | 7012 | 14632 |
| Water removed | kg | 291 | 573 | 435 | 906 | 988 | 1368 |
| Drying period | - | Oct. 8-14 | Oct. 5-14 | Oct. 8-14 | Oct. 2-12 | Sept. 20-30 | Sept.25-Oct.13 |
| Fan operating time | hr | 125 | 221 | 149 | 236 | 240 | 411 |
| Drying rate | kg $H_2O$/hr | 2.33 | 2.59 | 2.91 | 3.83 | 4.11 | 3.32 |
| Electric power requirement* | kW | 0.19 | 0.21 | 1.38 | 1.59 | 0.24 | 1.7 |
| Total elektric energy consumption | kWh | 23.7 | 46.4 | 205.6 | 375.2 | 57.6 | 698.7 |
| Specific energy requirement | kWh/kg $H_2O$ | 0.08 | 0.08 | 0.47 | 0.41 | 0.06 | 0.51 |
| Specific energy cost** | US $/ton | 0.14 | 0.27 | 0.82 | 1.50 | 0.21 | 1.31 |

* efficiency of the fan $\eta = 0.6$ ** on the basis of on farm use: 0.03 US $/kWh

**Table 2. Paddy condition after the 1981 and 1982 low-temperature in-bin drying tests compared with a naturally dried control sample**

| Test Year | Storage Bin No. | Bulk Density (g/ml) |  | Dehulling Rate (%) |  | Polishing Rate (%) |  | Milling Yield (%) |  | Cracking Ratio (%) |  | Germination Rate (%) |  | Acid value (mg KOH/g) |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  | C | LTD | C | LTD | C | LTD | C | LTD | C | LTD | C | LTD | C | LTD |
| 1981 | 1 | 0.57 | 0.57 | 78.8 | 78.9 | 90.3 | 89.3 | 71.2 | 70.4 | 8 | 8 | 69 | 71 | 8.6 | 9.1 |
|  | 2 | 0.56 | 0.57 | 77.0 | 76.0 | 90.2 | 90.4 | 69.5 | 68.7 | 7 | 6 | 70 | 67 | 8.3 | 9.6 |
|  | 3 | 0.57 | 0.57 | 78.6 | 78.7 | 90.9 | 90.4 | 71.4 | 71.1 | 6 | 8 | 83 | 78 | 9.1 | 9.8 |
|  | 4 | 0.56 | 0.56 | 77.9 | 77.9 | 90.6 | 89.0 | 70.6 | 69.3 | 7 | 6 | 79 | 78 | 8.7 | 10.1 |
| 1982 | 1 | 0.55 | 0.55 | 78.3 | 78.4 | 90.8 | 89.7 | 71.1 | 70.3 | 11 | 9 | 75 | 77 | 9.0 | 9.6 |
|  | 2 | 0.54 | 0.55 | 78.9 | 78.9 | 89.9 | 89.5 | 70.9 | 70.6 | 8 | 6 | 78 | 79 | 9.1 | 10.5 |

C Control sample LTD Low-temperature dried

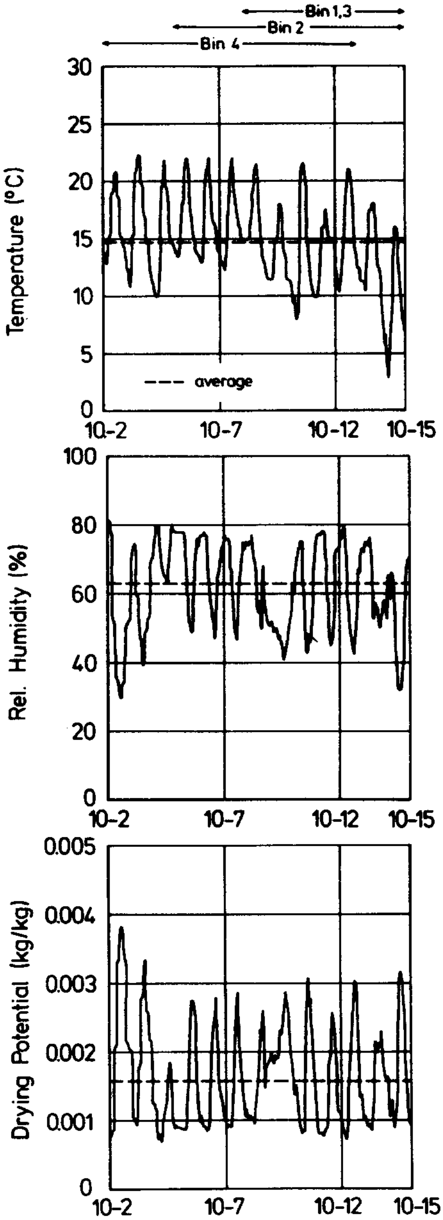

**Fig. 2. Temperature, relative humidity and drying potential of the ambient air during the 1981 (October 2-15) low-temperature drying tests**

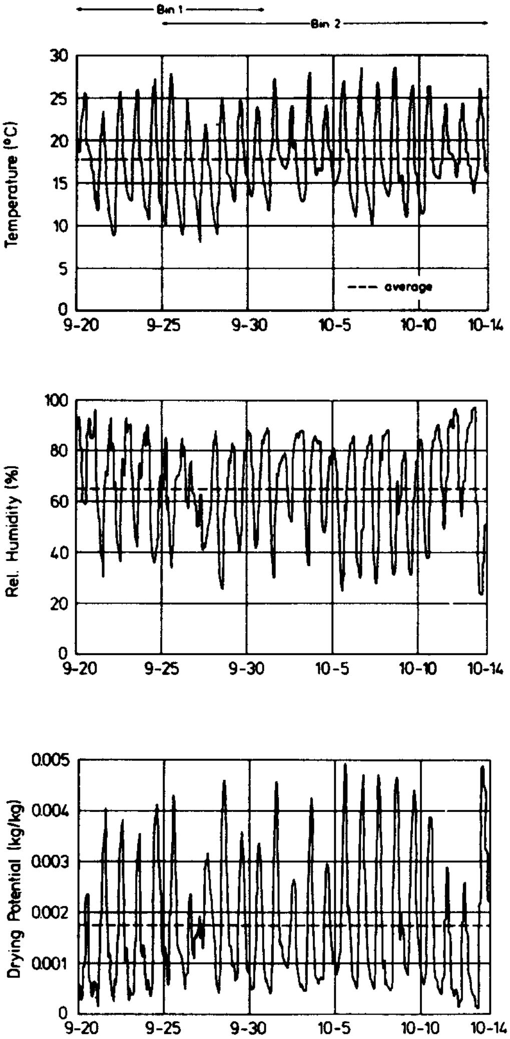

**Fig. 3. Temperature, relative humidity and drying potential of the ambient air during the 1982 (September 20-October 14) low-temperature drying tests**

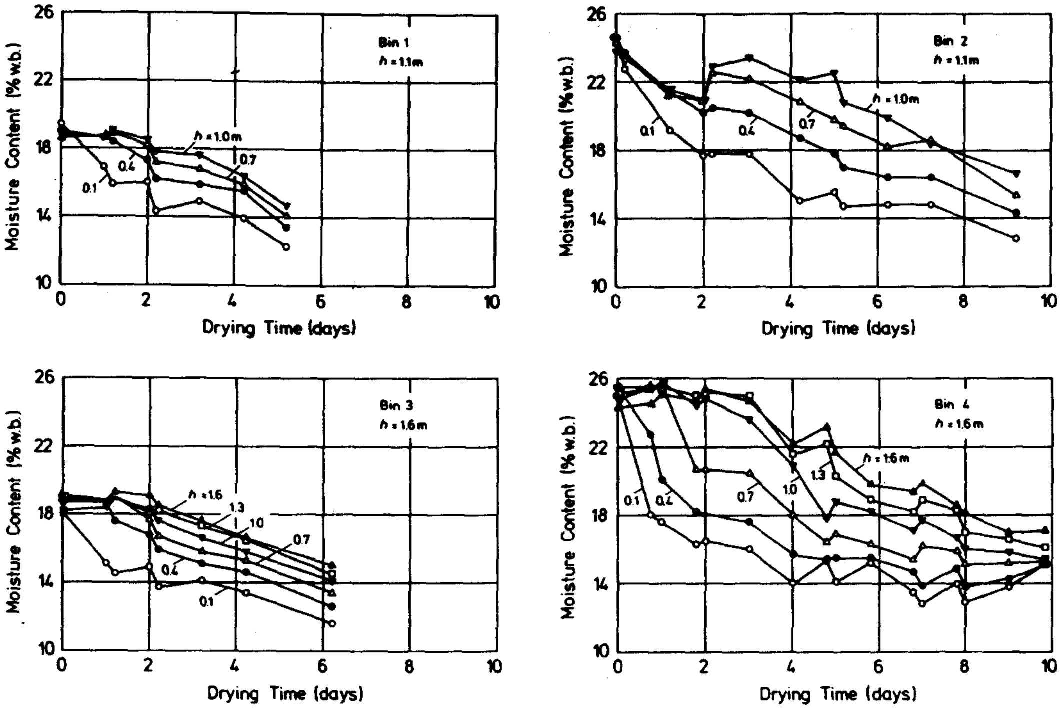

**Fig. 4. Changes in the moisture content of paddy in the bulk during the 1981 low-temperature drying tests**

Airflow rate: Bins 1 and 2: 5.0$m^3$ air/$m^3$ paddy/*min*, Bins 3 and 4: 6.9$m^3$ air/$m^3$ paddy/*min*

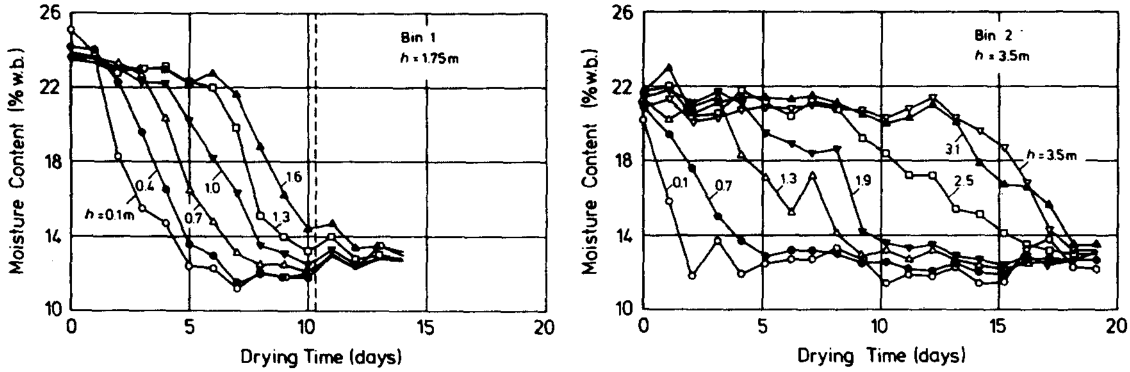

**Fig. 5. Changes in the moisture content of paddy in the bulk during the 1982 low-temperature drying tests**

Airflow rate: Bins 1 and 2: 3.0$m^3$ air/$m^3$ paddy/*min*

measured data had to be converted to the same fan efficiency in order to determine the influence of the various drying parameters upon the electricity required and the energy consumption. The data summarized in Table 1 were calculated by assuming that the fans had a 60% efficiency. The low-temperature drying tests have shown that the energy costs for low-temperature paddy-drying are considerably less than those required for high-temperature dryers. The lowest specific energy requirement can be reached by loading the bin to a depth of between 1.1 and 1.75 *m* and by operating the system with airflow rates of 3.0 to 5.0 $m^3$ air/$m^3$ paddy/*min*, equivalent to an air speed of 0.09 *m/s*.

For Korean farmers with a total paddy production of less than 6 tons, corresponding to approximately 1 hectare,(1,2,3) a low-temperature dryer with a bulk depth of about 1.5 *m* and an airflow rate equivalent to an air speed of 0.1 *m/s* seems to be the most practical solution involving extremely low energy costs. The bulk depth must be increased when drying larger quantities of paddy with low-temperature drying systems because the capital costs fall considerably as the bulk depth rises. If the system's capital and operating costs are allowed for, a bulk depth of 3.0 to 4.0 *m* seems to be more economic for installations in storehouses. In fact, the tests have shown that the specific energy requirement is greatly influenced by larger bulk depths. Nevertheless, the specific energy costs are still lower than for high-temperature drying.

**Quality**

Uniformity of drying and milling yield are the main criteria applied when evaluating the quality of the dried paddy. The tests have shown that low-temperature drying causes a uniform distribution of the moisture in the bulk. A little differences in the moisture between the air inlet and outlet were, of course, found but this is typical of all batch-drying systems. The paddy quality in terms of its bulk density, milling yield and cracking ratio is summarized in Table 2. All the tests have shown that low-temperature drying has no detrimental effects on these quality criteria. Nor was the germination rate significantly affected by low-temperature drying. A slight increase in the acid values do not justify the conclusion that the paddy suffered serious deterioration.

## Conclusion

The following conclusions can be drawn from the results of the low-temperature in-bin drying tests conducted in 1981 and 1982.

Under Korean climatic conditions low-temperature in-bin paddy drying is a genuine alternative to the conventional high-temperature dryers in terms of its energy requirements, energy costs, the uniformity of moisture content and the quality of the dried paddy. The main advantage of this drying system is, however, the small capital investment. And low-temperature in-bin drying allows early harvesting and threshing of the wet paddy. Using airflow rates of 3-6.9 $m^3$ air/$m^3$ paddy/min., it was possible to dry paddy loaded to 3.5 *m* in depth to safe storage conditions in 5 to 17 days. Quality tests showed that low-temperature drying has no detrimental effects upon the milling rate, germination and acid value. The energy required to drive the fan and the energy costs are considerably less than for conventional high-temperature dryers.

Low-temperature in-bin drying of paddy seems to be the most suitable drying system for Korean farmers in terms of its capital investment, energy costs and labour input. If bins or other storage facilities are loaded to a depth of 1.5 *m* and an airflow rate of 3.0 $m^3$ air/$m^3$ paddy/*min* is applied, paddy with a moisture content of up to 25% w.b. can be dried to safe storage conditions without any rise of losses in quality. When larger quantities of paddy are dried, the bulk depth must be increased to 3.5-4.0 *m*, since the capital investment drops considerably as the bulk depth rises. This does increase the energy costs but the total drying costs, including capital and operating costs, are still lower than for high-temperature drying systems.

## Acknowledgements

The authors acknowledge their indebtedness to the German Agency for Telchnical Cooperation (GTZ) and the Korea Science and Engineering Foundation (KOSEF) for their support for this investigation. The research was conducted at the Korea Advanced Institute of Science and Technology (KAIST) under an R & D contract between GTZ and KOSEF as part of the technical cooperation between the Federal Republic of Germany and the Republic of Korea.

## 요 약

상온통풍에 의한 벼의 in-bin 건조에 있어서 건조시간, 에너지 소요량, 품질에 미치는 몇가지 건조조건(기후, 초기 수분함량, 벼의 수량 및 풍량)의 영향을 검토하였다. 철제 grain bin(지름 : 3.0*m*, 높이 : 5.0*m*) 네개를 이용하여, 1981년 및 1982년에 각각 수확한 물벼를 그해 수확기에 건조하였을 때, 벼의 수분함유량(19.2~25.5% W.b.), bin내에서의 벼의 높이(1.1~3.5*m*) 그리고 풍량(3.0~6.9$m^3$ air/$m^3$ paddy/*min*)에 따라 건조에 소요되는 시일은 5~17일이었다. 이와같은 조건의 범위에서는 우리나라 벼수확기의 가을 기후는 벼의 in-bin 상온통풍 건조에 알맞았으며, 최종수분 함량, 도정수율, 쇄미율, 발아율, 지방산가 등의 품질에서도 아무런 문제도 없었으며, 종래의 고온건조방법과 비교했을 때 에너지 소요량과 에너지 비용도 대단히 낮았다.

## References

1. Lee, C.H. and Chung, C.H.: *An Evaluation of Rice Post-Harvest Systems Interms of Grain Losses and Maximum Recoveries (Final Report)*, Seoul National Univ., Suewon (1978)

2. Anonym.: Ministry of Agriculture and Fisheries, *Yearbook of Agriculture and Fishery Statistics* (1981)
3. Pyun, Y.R.: In: *Prevention of Post-Harvest Loss of Grains at the Village Level (Final)*, KAIST Report 78-2001-2-1-1 (1981)
4. Cheigh, H.S.: *Prevention of Post-Harvest Loss of Grain at the Village Level*, KIST Report 78-2001-2-1 (1979)
5. Wenner, H.L.: *Berichte über Landtechnik*, No 45, Wolfratshausen (1955)
6. Maltry, W.: *Archiv für Landtechnik*, 3(2), 145 (1962)
7. Ekström, N. and Noren, O.: *Srudier over kalluft-storkning ar spannmal*, Specialmeddelande p. 23, Swedish Insti. of Agri. Engineering, Ultuna-Uppsala (1974)
8. Morey, R.V., Cloud H.A. and Hansen, D.J.: *Trans. of the ASAE*, 25, 1312 (1981)
9. Mühlbauer, W., Stahl, T., Hofacker, W. and Reisinger, G.: ASAE No 82-3006, Am. Soc. of Agri. Engineers, St. Joseph, Michigan (1982)
10. Foster, G.H.: *Agri. Engineering*, 34(10), 681 (1953)
11. Morey, R.V. and Peart, R.M.: *Trans. of the ASAE*, 14(5), 930(1971)
12. Shove, G.C.: ASAE-paper No 70-830, Am. Soc. of Agri. Engineers, St. Joseph, Michigan (1970)
13. Kuppinger, H., Müller, H.M. and Mühlbauer, W.: *Grundlagen der Landtechnik*, 27(4), 119 (1977)
14. Morrison, S.: *Agri. Engineering*, 35(10), 735 (1954)
15. Sorenson, J.W. and Crane, L.E.: Bulletin B-952 Texas Agri. Exp. Stn., Texas (1960)
16. Lee, S.W. and Chung, C.J.: *J. Korean Soc. Agri. Engineering*, 16, 691 (1974)
17. Chung, C.J.: J. *Korean Soc. Agri. Engineering*, 16, 11 (1974)
18. Chung, C.J. and Koh, H.K.: Simulation of natural air layer drying of rough rice, In: *Post-Production Rice System in Korea (Final Report)*, College of Agri., Seoul National Univ., Suewon (1983)
19. Cheigh, H.S., Rim, J.W. and Kim S.K.: *Korean J. Food Sci. Technol.*, 14, 271 (1982)
20. Morey, R.V., Cloud, H.A., Gustafson, R.J. and Petersen, D.W.: *Trans. of the ASAE*, 22(6), 1418 (1979)
21. Colliver, D.G., Barrett, J.R. and Peart, R.M.: ASAE-paper No 79-3013, Am. Soc. of Agri. Engineers, St. Joseph, Michgan (1979)
22. Pierce, R.O. and Thompson, T.L.: Part I and II, ASAE-paper No 78-3513 and 78-3514, Am. Soc. of Agri. Engineers, St. Joseph, Michigan (1978)
23. Foster, G.H. and Peart, R.M.: Agri. Information Bulletin No 401, Washington, D.C. (1976)
24. Mory, R.V., Cloud, H.A., Gustafson, R.J. and Petersen, D.W.: *Trans. of the ASAE*, 22(2), 409 (1979)
25. Chang, K.S., Kim, M.S. and Kim, D.M.: *Korean J. Food Sci. Technol.*, 11, 264 (1979)
26. Stenvens, J.B., Barrett, J.R. and Okos, M.R.: ASAE-paper No 78-3004, Am. Soc. of Agri. Engineers, St. Joseph, Michigan (1978)
27. Bakker-Arkema, F.W., Lerew, L.E., De Boer, S.F. and Roth, M.G.: Grain dryer simulation, Research Report No 224, Agri. Exp. Stn., Michigan State Univ., East Lansing (1974)
28. Sharp, J.R.: *J. Agri. Engineering Res.*, 27, 169 (1982)
29. Spencer, H.B.: *J. Agri. Engineering Res.*, 14, 226 (1969)
30. Bloome, P.D. and Shove, G.C.: *Trans. of the ASAE*, 15(2), 310 (1972)
31. National Office of Agri. Products Inspection (Korea): Agr. Product Inspection Manual (1981)
32. A.A.C.C.: Cereal Laboratory Methods, 7th ed., Am. Associ. of Cereal Chemists, St. Paul, Minn. (1962)

(Received November 27, 1984)