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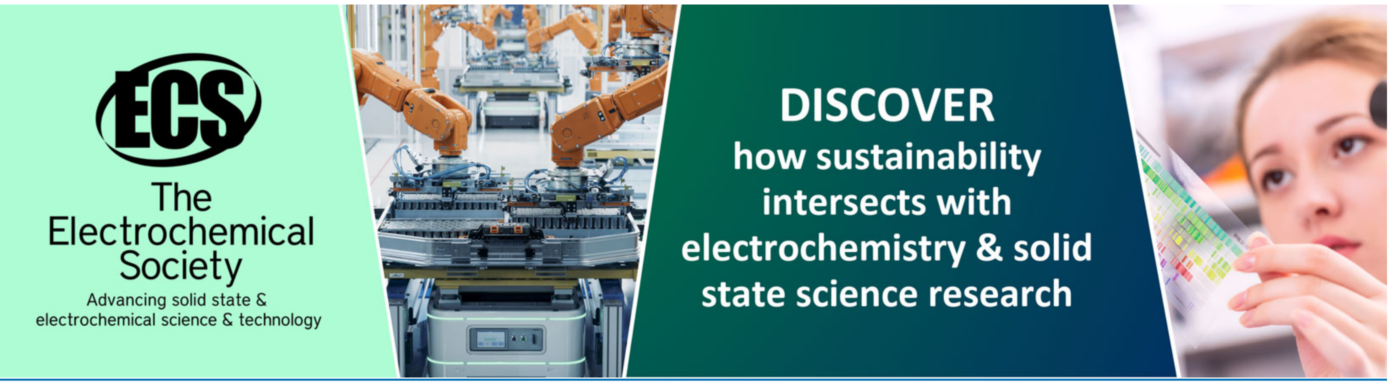

Experimental study on improving the drying uniformity in hot air cross-flow dryer

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Abstract. Drying is one of the important steps in the deep processing of agricultural and sideline products. It is a main tendency to research and develop the high-efficient and energy-saving drying pattern and technology. However, it is found that drying uneven phenomenon often exists in the material-drying oven in the production practice of hot air flow drying process. In order to explore the causes of the formation of uneven phenomenon, and to propose the ways to eliminate the inhomogeneity, experimental research was conducted concerning a multifunctional drying equipment with the hot air circulation. The temperature distribution uniformity and drying efficiency in the oven were tested under no-loaded and loaded conditions, in aspect of oven tray structure improving, wind direction switching and moisture controlling of exhaust air. Experimental results show that the drying inhomogeneity and thermal efficiency could be improved by the ways of changing the wind direction from cross-flowing to cross-swept-flowing, and as well as proper moisture controlling of exhaust air.

1. Introduction

Drying is one of the important steps of agricultural and sideline products processing. Researching and developing the high-efficient and energy-saving drying pattern and technology is the main development tendency of drying technology. Different materials are suitable for different drying methods, among which the hot air drying is applied most in the actual producing. However, several problems might exist such as low drying efficiency, low product quality and high energy consumption due to uneven distribution of air flow in the hot air cross-flow drying oven. These problems attract the attention of the expert in the academic and industrial fields [1].

Zhu W X *et al* [2] conducted the experiment about regularities of air speed distribution in the hot air cross-flow drying oven. It is found that the drying evenness phenomenon were related to air speed distribution. The uniform distribution of air speed is decisive factor of temperature. What's more, there are many common points between drying distributions without load. It's been found that the measurements of temperature and air speed in the hot air drying oven were hard to get, which form Yin Y *et al* [3]. Some researchers [4,5] discussed the way to access the temperature in the vegetable drying oven and the level of material's uniformity. At the same time, they tested the effectiveness of this way, which can improve efficiency in the development of drying equipment. What's more, they also offered steps to improve the air distribution uniformity in the drying oven by adding baffle boards. These research contents are based on experiments. The measurement of speed was limited, which will have a bad influence on the whole oven's uniformity. Facing complicated drying processing, some scholars established the models about heat transfer theory and mass transfer theory. They predicted the case of changing in the temperature of the material and moisture content on the drying processing. As for the phenomenon of drying unevenness, Huan Z G and Rumsey *et al* [6] did a research on numerical simulation by CFD. Zhao J H [7] and other researchers [8] who are from China Agricultural University established the CFD theoretic model of air speed field in the drying oven with composite boards. Compared to the test result, they found that simulation result was viable. Also, they got the main reason why air speed distribution unevenness lead to drying low efficiency and uneven drying processing. Msthioulakis [9] and other researchers did a research on flow filed condition about intermittent tray in the hot air drying oven. By using phonics program. Meng W W [10], Gabites [11] and other scholars [12] did a simulation about drying model and flow field in the atomizing drying oven. Lu R [13] and other researchers simulated the flow field air speed distribution in the condition of whether carry boards with uniform air in the vertical type dryer. They thought that the effect of carrying was obvious. Also, the height and smooth level of materials were related to the air speed filed.

It's obvious that everyone in academic field has reached an agreement that the main factor of drying unevenness was caused by the flow of hot air's uneven distribution. However, few people thought out the way to improve the uniformity of drying besides adding baffle boards with uniform distribution wind. This article is about some ameliorative way from the structure of drying oven. Researchers studied the way to improve uneven drying and evaluated the improved effect by experiments.

2. Experiment setup

The research object is multi-functional drying equipment in which wet material can be dehydrated by circulated hot air as shown in figures 1 and 2. The drying device is mainly composed of hot air stoves, fans for smoke, commutators, pipelines for wind, exhaust drying boxes and other parts. The hot air oven provided hot air to drying boxes. Drying boxes were cubes, of which length is 1.01 m, width is 0.85 m, and the height is 1.18 m. There are no more than 14 drying plates from bottom to top, the entrance of the hot air is hot air distributor in the bottom of oven.

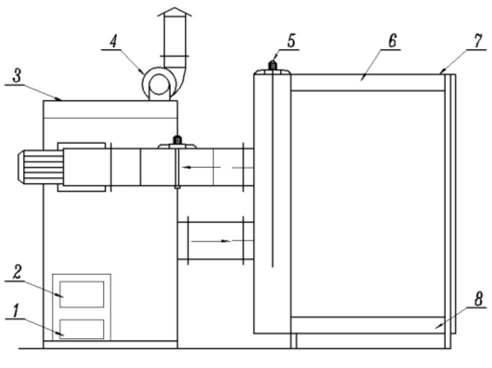


Figure 1. The structure diagram of hot air circulation dryer.

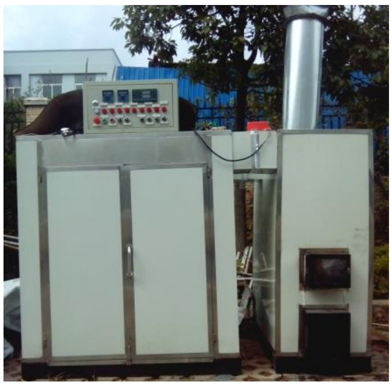


Figure 2. The photo of hot air circulation dryer.

The fresh broad bean, sliced fresh cabbage, cut new red peppers are used as drying material in the drying box's experiment. The measurement of temperature in the experiment came from Pt 100 hot resistance. And the measurement of humidity in the experiment came from PTS-3 transducer of air humidity. Both the hot resistance and the transducer are the parts of solar energy tester which is called TRM-2A produced by Jingzhou solar corporation. After 15 roads have been collected, the signal will be read by computers. And measurement of wind pressure came from K0603 aptitude pressure gauge.

3. Experiment methods

3.1. The experiment about unevenness in the primary drying oven
According to the research results, the fundamental cause of uneven drying is uneven distribution of internal flow field. And the uneven distribution is in the state of no load and cold condition. Next, difference is increasing after adding drying material, which may change the degree of this uneven distribution. Drying efficiency during given time can be obtained by measuring the dehydration rate of material on each plate, to study the unload condition and load condition by experiments, and get the way to improve the uniformity in the time and space. The way is about hot air baffle-flow.

3.2. The way to improve the efficiency of mixed hot air baffle-flow
To improve the drying plates, and change the effects of the hot air and material mass transfer, researchers changed the air direction from one-though cross-flow to the pattern of cross-flow mixed with baffle-flow. To explore whether different drying plate structures can bring different baffle-flow effects, the researchers did three ways to do experiments. The first was about single baffle-flow, the second was about double baffle-flow and the last was about double baffle-flow with micropore. Three hot air flow patterns can be shown as figure 3. Leaving 8 cm to lay cut-through flaps in the first level of drying plate's left space. Leave 8 cm to lay flaps in the second level of drying plate's right space. And do like this repeatedly, lay material in the remaining space to form double baffle-flow, trepan in the double baffle-flow boards and forming double baffle-flow with micropore, and lay drying plates in the 2th level, 5th level, 9th level and 13th level in the drying oven. And there were not yet drying cabbage which weighed 6 kg and its height was 5 cm probably in every plate. To represent the degree of the unevenness, researchers placed 3 temperature probes in every drying plate, which is shown in figure 4.

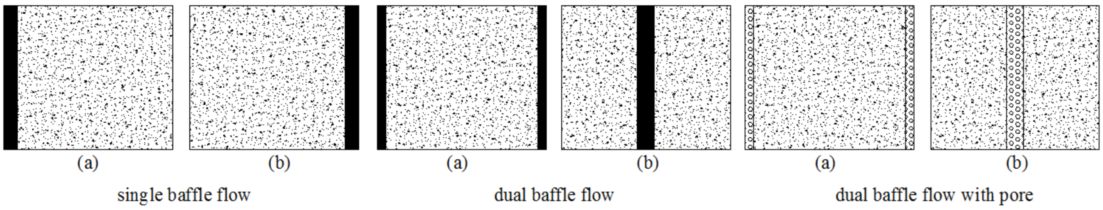
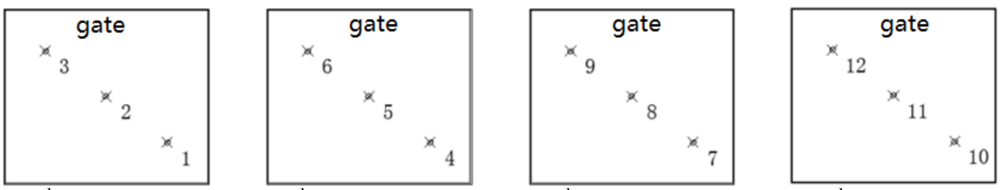


Figure 3. Three tray improvement schemes of baffle-flow in the dryer.

In the place of temperature probes in the plate, there are 3 temperature probes laid in upper left, central place and low right in every level as shown in figure 4.



2^{ed} drying plate 5^{th} drying plate 9^{th} drying plate 13^{th} drying plate

Figure 4. The location of temperature probes on the dryer tray.

4. Results and discussion

4.1. The unevenness about experiment in the primary drying ovens
To represent the degree of the unevenness in the no-load drying plates, the researchers placed temperature probes in five places of the last bottom in the drying plates, measuring the temperature change in a constant time and getting the collected wind data. The subscripts 1-5 in the temperature mark represent the top left corner, left bottom, central place, lower right corner and top right corner in turns as shown in figure 5. The recurrent air got into the entrance at the speed of 12 m/s, and it was

heated continuously. The change about temperature in the 10 minutes is shown in figure 6. Obviously, when the temperature of hot air was from 40℃ to 65℃, the rising rate of temperature in central place was the lowest. And the result was in a condition of unload. The rate in central place was father lower than others. The temperatures of point 1, point 2 and point 4 were near, which indicated that the blast capacity in central place was lower than other places. Also, it provides an explanation why the place of wet island is in central place.

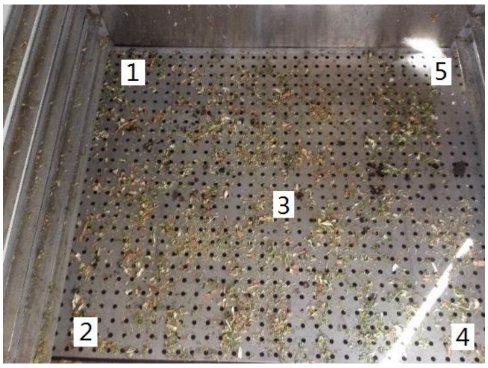


Figure 5. The location of temperature sensors under no-load.

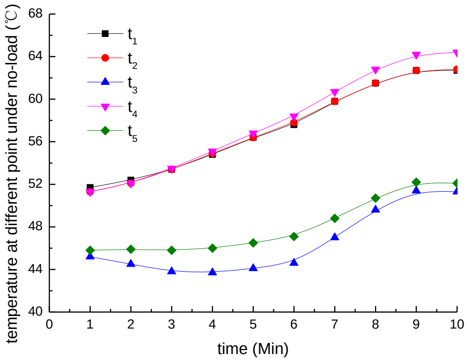


Figure 6. The history of temperature change on the dryer tray under no-load.

To improve the unevenness in every level's drying plate, researchers took the sliced fresh cabbage as not-yet-drying material. There are 100 kg wet materials totally in 14 1evels. Besides the 6th level and the 7th level without plates, there are 8.33 kg material in every plate, and the material was laid averagely in the plates which are 9.6 m^2. The total time about drying was 425 minutes, the temperature of hot air was set as different levels, as shown in figure 7. What's more, in the former 3 hours, the patterns about wind access in the bottom and top was 6:4. In the aspect of wet ejectment, there are 150 minus carrying half wet ejectment later. The weights of material in the 2ed level, 5th level, 9th level and 13th level drying plates were weighted in the drying processing, which was shown in figure 8. The change about dehydration rate with time is shown in figure 9. The loaded 12 levels material weights and dehydration rates in the end of drying processing are shown in figure 10. The wet ejectment temperature and wet gas in the drying processing are shown in figure 9. By analysing these figures, we know that the dehydration speeds in the 13th level and 2th level are near, and the speeds are father higher than the drying speeds of the 5th level and the 9th level. What's more, the drying speed of the 9th level is the lowest in four levels measured material. Taking measurement at the beginning of drying, researchers found that the dehydration rate of 9th level was less than 0, which indicated that the parts didn't lose water in former two hours. And it absorbed the water from other parts. At the end of drying, the weights of middle six levels' material were obviously higher than the weights of material which was near to the entrance in the bottom and top. And the dehydration rates of 9th level and 10th level were the lowest. The reason of this is that when hot wind crossed drying plates from one level to another, the accumulation of wind was increasing, and the speed of wind was lower and lower, the heat transfer and mass transfer speeds of hot air and material was slower and slower. However, switch the direction of wind entrance remitted the drying speed's reduction from one direction. And the drying speeds of two ends were higher than central level's. The 9th level and 10th level were near to the place of central top. Because the wind from top was lower, and the drying speeds of them were the slowest.

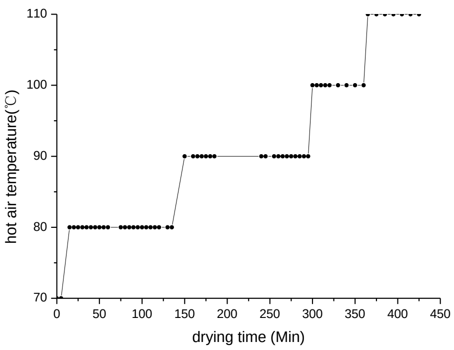


Figure 7. The temperature history of dryer inlet air.

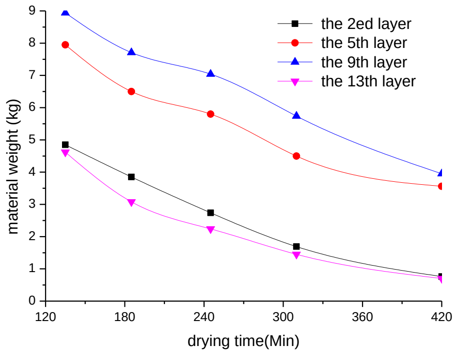


Figure 8. The material weight of the typical four layers.

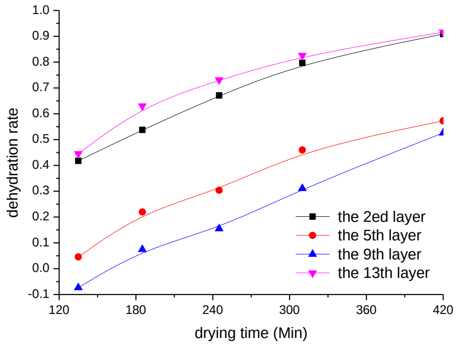


Figure 9. The material dehydration rate history of the typical four layers

In the aspect of material's dried condition, the average dehydration rate of 12^{th} level material in drying plate was 71.1%. The average dehydration rates of the 2^{ed} level, the 5^{th} level, the 9^{th} level and the 13^{th} level were 73.0% in end. And the result of this was near to the whole average dehydration rate. Therefore, the rate was representative. Researching the dehydration rate condition in drying processing deeply, the dehydration rate of drying material on 13^{th} level plate reached 73.1% at the time of 345 minutes, the dehydration rate of the 2^{ed} level reached 73.0%. Therefore, the material in the top and bottom drying plates finished the drying processing nearly in the farmer 4 hours. And the later 3 hours were useless for the drying processing, which caused the low efficiency and high energy consumption doubtlessly.

It can be found from wet ejectment curve that the temperature of the dried waste gas was higher than 40℃, and its humidity was less than 40%, as shown the figure 11. In this case, there is a lot of recyclable wasted. Therefore, ejecting heat completely can't improve the unevenness and lower the utilizing efficiency. Also, the condition of ejecting heat in half was the same with the condition of ejecting heat completely.

What's more, researchers observed the form of the material and found that the cabbage in the edge of plates has been dried up. They found this by getting the weight of the material on the 2^{ed} level, the weight of the 5^{th} level, the weight of the 9^{th} level and the weight of 13^{th} level. The division line about drying and wet qualitatively are drawn. And the moist island area of every level are shown in figure 12. The percentage of first gate area is probably 22%, the percentage of second gate area is probably 32%, the percentage of third gate area is probably 46%, the percentage of fourth gate area is probably 62%.

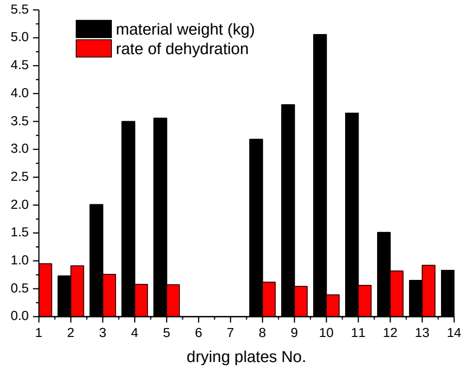


Figure 10. The distribution of dehydration rate at the drying end moment.

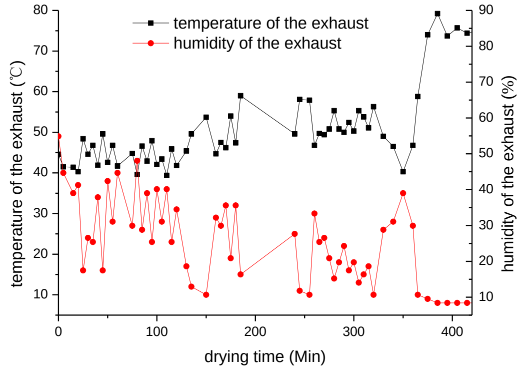


Figure 11. The temperature and humidity of exhaust air.

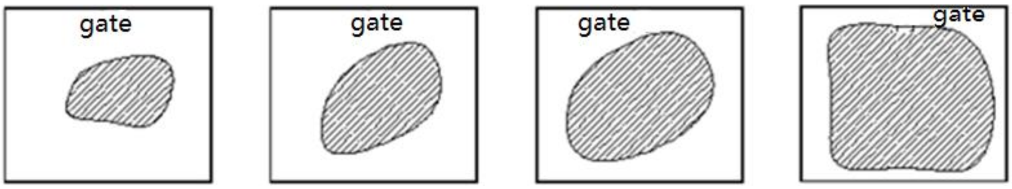


Figure 12. The wet island area in the four typical layers.

4.2. The experimental results of baffle-flow evenness

Researchers did the experiment by 3 ways that were changing hot air flow to cross-flow and baffle-flow. They had been drying 13 minutes at the temperature of 80℃, and they got 12 temperature conditions of measuring points, which was shown in figure 13. Then, the drying plates were taken out, and next, the weight of the material in the plates was measured and dehydration rate was calculated. The temperature distribution and dehydration rate of every plate are shown in figures 14.

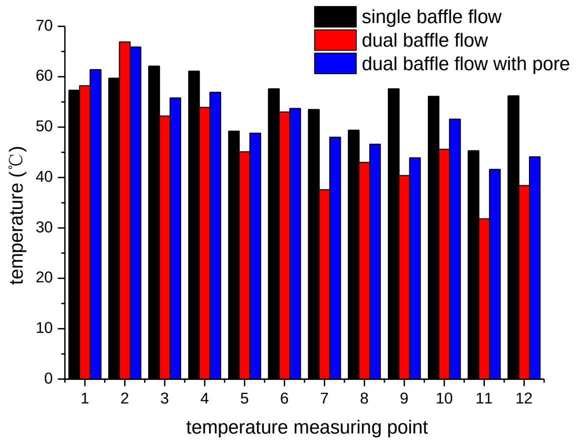


Figure 13. The temperature distribution under three baffle-flow scheme.

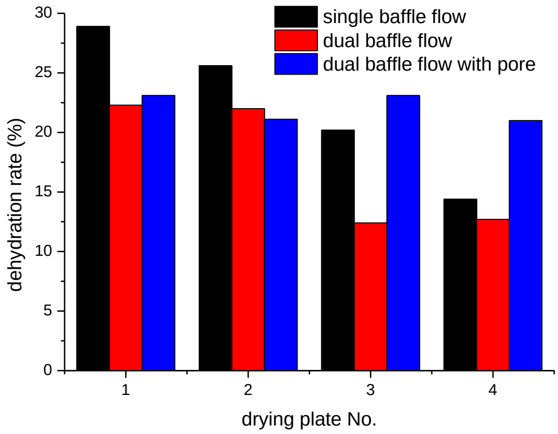


Figure 14. The dehydration rate distribution under three baffle-flow scheme.

The definition of unevenness as follows:

To remove the influence of different average data, RSD was defined as no-dimension parameter.

$$RSD = S/\bar{x} \times 100\% \tag{1}$$

The researchers calculated the uneven temperature and RSD in every plate by different ways of baffle-flow, and the results are shown in figures 15 and 16. In the condition of single baffle-flow, the uniformity of the first level plate was the best, the drying uniformity of other three level plates were the worst oppositely. In the condition of double baffle-flow, the uniformity of the 3th level was even, while the other plates' uniformity was worse. In the condition of double baffle-flow with micropore, except that the first level's uniformity was worse, the others were the best. In the aspect of the temperature distribution in the plates, the temperature of point 3, the temperature of point 4, the temperature of point 10 were the highest in the case of single baffle-flow. We can find that the highest temperature point is bended from figure 15, which indicated that the guide effect of convection current was obvious. In the condition of double baffle-flow the temperature of the point 2 and the point 8 in central place were highest. And the temperature of the point 5 and the point 11 were the lowest. However, the point 5 and point 11 were also in the place of central. From what discussed above, we know that the form of the case is double baffle-flow. In the condition of double baffle-flow with micropore, the case of the highest temperature and the lowest temperature were same to the double baffle-flow. However, the whole uniformity was obviously higher than the double baffle-flow. Because of the small different value of temperature mean value, the RSD change regular is same to the temperature unevenness. Only in the case of double baffle-flow, the unevenness was more obvious. From what has been discussed above, the unevenness of average temperature distribution was 3.4℃ in the case of single baffle-flow. The unevenness of average temperature distribution was 3.9℃ in the case of double baffle-flow. And the unevenness of average temperature distribution was 2.9℃ in the case of double baffle-flow with micropore. On the other hand, RSD were 6.26%, 8.18%, 5.73%, respectively. Obviously, in the aspect of temperature distribution, the best ways to improving drying plates' temperature unevenness and the temperature unevenness between plates were double baffle-flow with micropore.

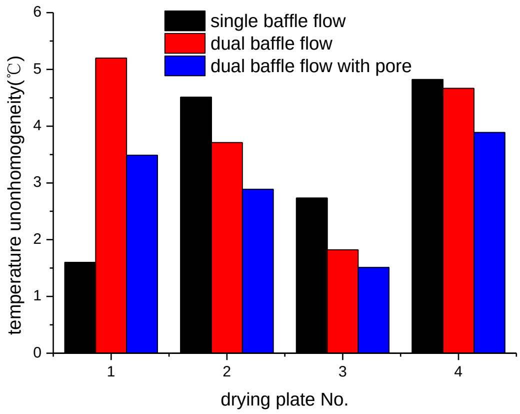


Figure 15. The temperature unevenness under the three baffle-flow scheme.

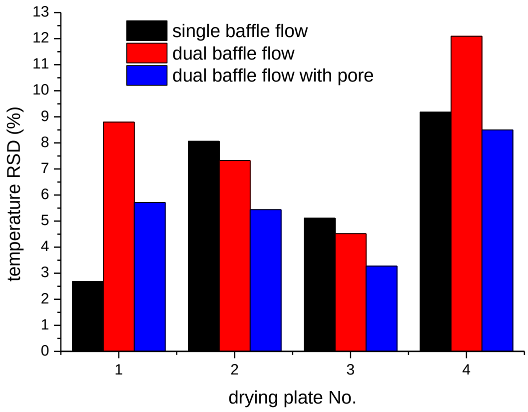


Figure 16. Temperature RSD under the three baffle-flow scheme.

By comparing the own dehydration rates 135 minutes later, the average dehydration ratesof single baffle-flow was 22.2%, the dehydration rate of double baffle-flow was 17.4%, and the average dehydration rate of double baffle-flow with micropore was 22.1%. RSD of single baffle-flow was 4.98%, RSD of double baffle-flow was 4.80%, and RSD of double baffle-flow with micropore was1.03%. However, before adding baffle-flow and in the case of hot air cross-flow, for the sane count of material, the average dehydration rate of the 2th level, 5th level, 9th level and 13th level was all 20.89% after 135 mins. And RSD was all 22.3%. Obviously, the absolute dehydration rate of double baffle-flow was the lowest, which even lower than the unimproved patterns. And the dehydration rates of other two ways were close, which was 5% higher than double baffle-flow probably, and 1.3% higher than unimproved way. However, in the aspect of uniformity of dehydration rate, the uniformity index after baffle-flow was improved largely. The index from 22.3% was up to 5%, and the index in the condition of double baffle-flow was up to 1%.

Judging from temperature distribution cases comprehensively, the best ways to improve the uniformity of drying plates and the uniformity between plates are double baffle-flow with micropore, although there are some bad effects from baffle-flow transformation, such as the reduction of drying area and the increasing of wind resistance. And by calculating, researchers found that the reduction of three ways was 0.8%, 1%, 1%, dividedly. The cases above can be accepted in engineering. However, the double baffle-flow with micropore can control the areas with micropore, which can deduce the wind resistance rather than increasing. Therefore, the bad effects of three ways can be ignored.

5. Conclusions

- For the original drying ovens, the temperature in central place of every level's drying plate was lower than bordered areas' temperature in the condition of load and unload. When hot air crossed different level's drying plates, the wind resistance increased gradually and the drying speed of material got more quickly, and the material was close to the entrance. Therefore, changing the entrance of wind and bringing wind commutatively can improve drying efficiency. Also, it can remit the efficiency deduction with levels. Drying unevenness not only caused the drying speed of several levels' material which was close to the entrance 40% lower than other levels' material, but also added the energy consumption. And it reduced the efficiency of drying.
- Researchers did a transformation on the drying plates in the drying ovens. They found the temperature extreme values appeared commutatively from the highest point and the lowest point. They also found the forms of single baffle-flow and double baffle-flow. And they found that these ways can guide the hot air flow direction well.
- The three ways of baffle-flow transformation improved the unevenness of drying. And the reduced areas no more than 1%. Comparing three ways of efficiency improvement transversely, and in the aspect of temperature distribution, researchers found that the double baffle-flow with micropore could improve the temperature uniformity in the drying plates. The double baffle-flow with micopore also can improve the unevenness between drying plates well. In the aspect of uniformity of dehydration rates, the index after baffle-flow was improved largely. And the improvement rate was from 22.3% up to 5%. What's more, under the pattern of double baffle-flow with micropore, the improvement rate was 3%.
- From comprehensive analysis, researchers found that the best way to improve the uniformity in drying plates and evenness between plates is double baffle-flow with micropore. And by controlling the area with micropore, the count of micropore in the double baffle-flow can reduce wind resistance and energy consumption of draught fan. Therefore, double baffle-flow with micropore is a very beneficial way to improve drying efficiency.

Acknowledgments

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