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COMPUTER CONTROLLED ACTIVE YEAST DRYING

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
THE MIDDLE EAST TECHNICAL UNIVERSITY

BY

HAMİ ALPAS

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE
OF
MASTER OF SCIENCE
IN
THE DEPARTMENT OF FOOD ENGINEERING

JULY 1995

Approval of the Graduate School of Natural and Applied Sciences

Prof. Dr. İsmail Tosun
for Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science.

Prof. Dr. Ali Esin
Head of Department

This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

Prof. Dr. Faruk Bozoğlu
Co-Supervisor

Prof. Dr. Mustafa Özilgen
Supervisor

Examining Committee Members

Prof. Dr. Ali Esin

Prof. Dr. Mustafa Özilgen

Assoc. Prof. Dr. Alev Bayındırlı

Assist. Prof. Dr. Candan Gürakan

Instructor Dr. Sinan Katnaş

ABSTRACT

COMPUTER CONTROLLED ACTIVE YEAST DRYING

Alpas, Hami

M.S., Department of Food Engineering

Supervisor: Prof. Dr. Mustafa Özilgen

Co-Supervisor: Prof. Dr. Faruk Bozoğlu

July 1995, 58 pages

Drying and death rates of baker's yeast were studied in a computer controlled laboratory scale tunnel dryer with varying air velocity and temperatures within the range of 40 - 60 °C and 2.0 - 3.0 m/s. Two falling rate periods were observed during the drying process. A single first order expression described the death rate of the microorganisms during both drying phases. Arrhenius type expressions described the effects of the temperature on the first falling rate drying period and death rate constants. Compensation relations were also found between the parameters of these Arrhenius expressions. A single linear relation was observed between the first falling rate period drying constant and the death rate

constant at 2.5 and 3.0 m/s of air velocities. A similar relation was also observed with the data obtained at 2.0 m/s air velocity. It was also concluded that the death rate of yeast is proportional with the air velocity.

The second falling rate period was a diffusion controlled process. It was confirmed by the experimental results that the velocity of air flow did not affect the drying rate constants in the second falling rate period. Within the range of the experiments no temperature effects were also observed on the second falling rate period drying constant.

Keywords: Baker's yeast, Drying, Modeling, Microbial Death

ÖZ

BİLGİSAYAR KONTROLLÜ AKTİF MAYA KURUTULMASI

Alpas, Hami

Yüksek Lisans, Gıda Mühendisliği Bölümü

Tez Yöneticisi: Prof. Dr. Mustafa Özilgen

Ortak Tez Yöneticisi: Prof. Dr. Faruk Bozoğlu

Temmuz 1995, 58 sayfa

Bu çalışmada, bilgisayar kontrollü kurutma tünelinde ekmek mayasının kurutma ve ölüm hızları 40-60 °C sıcaklık ve 2.0-3.0 m/s hava hızı aralığında incelenmiştir. Kurutma sırasında, iki fazlı azalan hız devresi gözlenmiştir. Her iki fazda da mikroorganizmaların ölüm hızı basit birinci derece denklemle tanımlanmıştır. Sıcaklığın, birinci ve ikinci azalan hız devresi sabitleri ve ölüm hızı sabiti üzerindeki etkisi Arrhenius denklemiyle tanımlanmıştır. Ayrıca Arrhenius denklemi parametreleri arasında telafi denklemi bulunmuştur. Birinci azalan hız devresi sabiti ve ölüm hız sabiti arasında kurutma hava hızı 2.5 ve 3.0 m/s'de doğrusal bir ilişki gözlenmiştir. Aynı ilişki kurutma hava hızı 2.0 m/s'de

elde edilen veriler için de gözlenmiştir. Çalışma sonuçlarına göre, ekmek mayasının ölüm hızı, kurutma hava hızı yavaşladığında azalmaktadır.

İkinci azalan hız devresi difüzyon kontrollü süreçtir. Deneyler sonunda, kurutma hava hızının ikinci azalan hız devresine etkisinin olmadığı gözlenmiştir. Ayrıca yapılan deneylerde, sıcaklığın da ikinci azalan hız devresine bir etkisinin olmadığı gözlenmiştir.

Anahtar Kelimeler: Ekmek Mayası, Kurutma, Modelleme, Mikrobik Ölüm

ACKNOWLEDGMENTS

I wish to express my deepest gratitude to Prof.Dr.Mustafa Özilgen for his valuable guidance, continued advice and suggestions throughout the study.

I am also grateful to Prof.Dr.Faruk Bozoğlu for his continuos help and support in all phases of this study.

I would like to acknowledge Instructor, Dr. Sinan Katnaş for his great help and friendship during all phases of this work.

Thanks go to Nüzhet Ertugay and Sibel Özilgen for their great help together with all my friends in the Department of Food Engineering.

Finally, I would like to thank my family for their support, encouragement and patience.

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w	Dimensionless weight
w^*	Equilibrium moisture content
k_w	First falling rate drying constant (min^{-1})
k_{wo}	Pre-exponential drying rate constant (min^{-1})
E_{aw}	Activation energy for drying model (J / g.mol)
R	Ideal gas law constant (J / g.mol K)
T	Temperature (K in Arrhenius Plot, °C in elsewhere)
t	Time (min)
α	Constant in equation 3 (g.mol / J.min)
β	Constant in equation 3 (min^{-1})
k_{w2}	Second falling rate drying constant (min^{-1})
x	Microbial concentration (cfu / g dry yeast)
x_o	Initial microbial concentration (cfu / g dry yeast)
x_f	Final microbial concentration (cfu / g dry yeast)
k_d	Death rate constant (min^{-1})
k_{do}	Pre-exponential death rate constant (min^{-1})
E_{ad}	Activation energy for microbial death model (J / g.mol)
δ	Constant in equation 6 (g.mol / J.min)
ϕ	Constant in equation 6 (min^{-1})

$k_{w\ mean}$ Arithmetic mean of first falling rate drying constant (min^{-1})

d_i^2 Square of the deviation of the actual values around the regression line

r Correlation coefficient

v Drying air velocity (m/s)

CHAPTER I

LITERATURE SURVEY

Mathematical modeling is important for interpreting the experimental data and also for understanding the whole process.

There is almost no quantitative information in the literature relating the death and drying rate constants of the compressed yeast during active dry yeast production process. In the presented research drying and death rates of the baker's yeast with varying air temperature and velocity is studied and relations are be sought between the death and drying rate constants.

2.1. Active Dry Yeast (ADY):

Production of the baker's yeast has been reviewed in numerous references (Ponte and Tsen, 1978; Peppler, 1979; Reid, 1982; Reed and Nagodawithana, 1991). During the last century the major advances in the production of baker's yeast have been the following:

i) Aeration:

The stimulating effect of aeration on yeast growth was well known toward the end of the nineteenth century, and continuous aeration of mashes was used in Britain in 1886.

ii) Fed-batch Process:

The use of incremental feeding was introduced between 1910 and 1920 by Danish and German scientists.

iii) Molasses:

During the 1920's and 1930's, the grains were slowly replaced by molasses as carbon and energy source for yeast growth.

iv) Active Dry Yeast:

Progress was made in the late 1930's in the drying of compressed yeast (CY) to the more stable active dry yeast (ADY). Slow but continued progress in the drying methods led to the point where ADY has replaced CY in several bakery applications, particularly in institutional baking and pizzerias.

v) Automation:

During the past decade there has been a rapid shift to automatic control of fermentation.

In a typical process yeast is produced by fermentation, centrifuged, washed and concentrated into yeast cream of approximately 18 to 21% solids (Trivedi et al., 1989). It is then filtered in a filter press or vacuum filters. The filter cake is mixed with small amounts of water emulsifiers and oils and converted into compressed yeast pellets via extrusion. The compressed yeast is perishable and needs to be kept in closed packages in the refrigerator. Active dry yeast (ADY) is produced from the yeast cake by extrusion in the form of thin strands. These are air dried on a continuous belt or air-lift dryers. ADY with a solids content of 92-96% is shipped as sucs or in vacuum-packed or nitrogen flushed pouches. It does not require refrigerated shipment or storage. The yeast pellets can be tunnel dried to obtain a product containing less than 8% moisture without substantial loss of viability. ADY has been used extensively by retail bakers, institutional users and commissary type operations but it has not replaced CY in major wholesale bakeries. The comparison of active dry yeast with compressed and cream yeast is given in Table 2.1.

Table 2.1. Comparison of Active Dry Yeast (ADY) with Compressed and Cream Yeast (Trivedi et al., 1989).

	Compressed Yeast	Cream Yeast	Regular ADY	Protected ADY	Instant ADY
Moisture, %	70	82	7-8	5-6	4-5.5
Protein, dry basis, %	60	60	38-48	40-42	39-41.5
Shelf life at refrigeration (2°-4.5 °C)	3-4 week	3-4 week	6 months	9 months	1 year
Shelf life at room temperature (21 °C)	perishable	perishable	3 months	6 months	1 year

2.2. Drying Operation:

Drying is one of the most important preservation operations used in the food industry. Air, vacuum, spray and freeze drying are common ways of accomplishing the desired reduction of moisture content. The increased consumer awareness of food quality has emphasized the need to optimize the drying process. Computer-aided methods offer an opportunity to the food processors to design more efficient processes to produce products of the highest possible quality (Banga and Singh, 1994).

A large number of models have been proposed for air drying of biological materials (Russen and Hayakawa, 1977; Bruin and Luyben, 1980; Fortes and Okos, 1980; Chirife, 1983). In the recent literature, the suggested models and computational procedures vary from the fairly simple (Thijssen and Coumans, 1985; Sereno and Medeiros, 1990) to the complex (Whitaker, 1980; Chen and Pei, 1989; Sakai and Hayakawa, 1992).

The rate at which yeast cake may be dried varies greatly with the temperature and the moisture content of the drying stream, as well as with air velocity and the size and shape of the granulated yeast.

Drying of baker's yeast causes some damage to the cellular structure of some cells, including rupture of the cytoplasmic membrane, proteins, lipids, carbohydrates and polyphosphates (Bekker and Rappoport, 1987), the damage may also cause the death of cells; therefore an active dry yeast preparation can not be better than the compressed yeast that it is made from. It is generally believed that in a yeast drying process at moisture levels below 20%, respiration stops and cell constituents are leached if the yeast is rehydrated in water (Reed and Nagodawithana, 1991).

Drying of such porous solid structures may be analyzed in two stages: A constant rate period, followed by a falling rate period. Water movement during the constant rate period is assumed to be controlled by several factors, including capillary suction and diffusion. The capillaries extend from small reservoirs of water in the solid to the drying surface; surface tension of liquid is a controlling factor on the flow rate (Labuza and Simon, 1970). During the constant rate period of drying, the surface moisture concentration is reduced, but the concentration in the depths of the solid remains high. The resulting high diffusivities permit movement of the moisture to the surface as fast as it can be evaporated, and the rate remains constant. In the later stages of drying, water in the sub-surface reservoirs and consequently capillary flow and wetted area on the food surface decrease gradually, thus the unsaturated surface drying period starts, this is called the first falling rate period. After the wetted area on the surface totally disappears the liquid surface recedes into the capillaries and goes deeper as drying continues. This is called the second falling rate period, where evaporation occurs below the food surface and diffusion of vapor occur from the place of vaporization to the surface. If the initial constant drying is very rapid, the period of unsaturated surface evaporation may not appear, and the diffusion-controlled falling rate begins immediately after the constant rate period is completed (Treybol, 1980).

With the depletion of the sub-surface water reservoirs the mechanical structure collapses and the food undergoes shrinkage. In some foods subjected to drying, the shortening of the path length for water migration may offset the reduction in matrix porosity when shrinkage occurs(Labuza and Simon, 1970).

The mechanism of drying in slow drying non-porous materials, such as soap, gelatin, glue, and the later stages of drying of clay, wood, textiles, leather, paper, foods and starches is liquid diffusion (Geankoplis, 1983).

2.3. Computer Controlled Drying:

Measuring and analyzing real world conditions has always been a major component of research, design, testing, and manufacturing. Measuring voltage, temperature, pressure or other physical phenomena, data acquisition is the process of converting sensory or transducer signals into data that can be processed and analyzed on a computer (Teixeira and Shoemaker, 1989).

Before the advent of personal computer, data acquisition was primarily the domain of expensive and specialized test equipment as well as mini computers and mainframes but the personal computer has changed all that. While early 8-bit personal computers had limited data acquisition capabilities, today's 16-bit and 32-bit machines offer the power and flexibility to handle great majority of data acquisition tasks (Teixeira and Shoemaker, 1989).

Data acquisition involves measuring a physical variable such as temperature, pressure or voltage by using sensors or transducers. The captured signals are then conditioned either by a separate unit or by one built into a stand-alone data acquisition unit. The signal is then converted to digital form and the data is manipulated and displayed on a computer equipped with data acquisition software.

Regardless of the application, a data acquisition process is composed of four basic components:

i) Measurement of the physical conditions using sensors or transducers.

ii) Conditioning the signal.

iii) Analog to digital (A/D) conversion of the signal.

iv) Interface to the computer (including both hardware and software).

Sensors and transducers generate an electrical signal that usually requires some form of conditioning before it can be processed by the A/D converter and other processing components of the data acquisition hardware.

2.4. Mathematical Modeling:

A series of data can easily be interpreted by mathematical modeling.

2.4.1. Drying Model:

Weight loss in the first falling rate period was modeled as:

$$\frac{dw}{dt} = - k_w (w-w^*) \qquad (1)$$

An Arrhenius type of an expression was used to model the temperature effects on parameter k_w

$$k_w = k_{wo} \exp \left[\frac{-E_{aw}}{RT}\right] \qquad (2)$$

The constants of the Arrhenius expression were interrelated by:

$$\ln k_{wo} = \alpha E_{aw} + \beta \qquad (3)$$

which is referred to as a compensation relation.

2.4.2. Microbial Model:

Under ordinary conditions, lethality of microorganisms can be characterized by a logarithmic death curve (Moats, 1971), in which the rate of death is a pseudo-first order reaction (Elizondo and Labuza, 1974). Mathematically this is represented by:

$$\frac{dx}{dt} = - k_d x \qquad (4)$$

Temperature effects on the death rate constant k_d is modeled with an Arrhenius expression (Bailey and Ollis, 1986):

$$k_d = k_{do} \exp \left[\frac{-E_{ad}}{RT} \right] \qquad (5)$$

The kinetic compensation relation for the constants of the Arrhenius expression of microbial death constant has been suggested in the previous studies (Özilgen and Özilgen, 1995) as:

$$\ln k_{do} = \delta E_{ad} + \phi \qquad (6)$$

CHAPTER II

MATERIALS AND METHODS

3.1. Experimental Set-up:

Tunnel drying experiments were made in a drying tunnel under computer control Figure 1. A laboratory scale (Sartorius, Germany, sensitive to 0.01 g) was placed in the central location of the drying tunnel (105 cm long, 7.2 cm internal diameter) and connected with a high performance A/D-D/A card to the IBM compatible computer (486 DX, 33 MHz, 260 MB Hard disk, 8 MB RAM). A total of ninety runs of drying experiments were carried out for 45, 60, 90, 120, 150 and 180 minutes with air flow rates of 2.0, 2.5 and 3.0 m/s at 40, 45, 50, 55 and 60 °C. The models for drying and microbial death were developed with these experimental data, then ten more runs of experiments were carried out with 2.25 and 2.75 m/s air velocity with randomly selected experimental periods and temperatures (Table A1) and the constants of the parameters of the same models were evaluated by regression under these conditions (Table A2 and Table A3). Relative humidity of the air was less than 5%. Temperature of air was measured with a temperature sensor (NEL, Turkey) placed in front of the sample holder. The weight of the samples, temperature and the velocity of the air stream was continuously monitored by the computer. The computer controlled the air

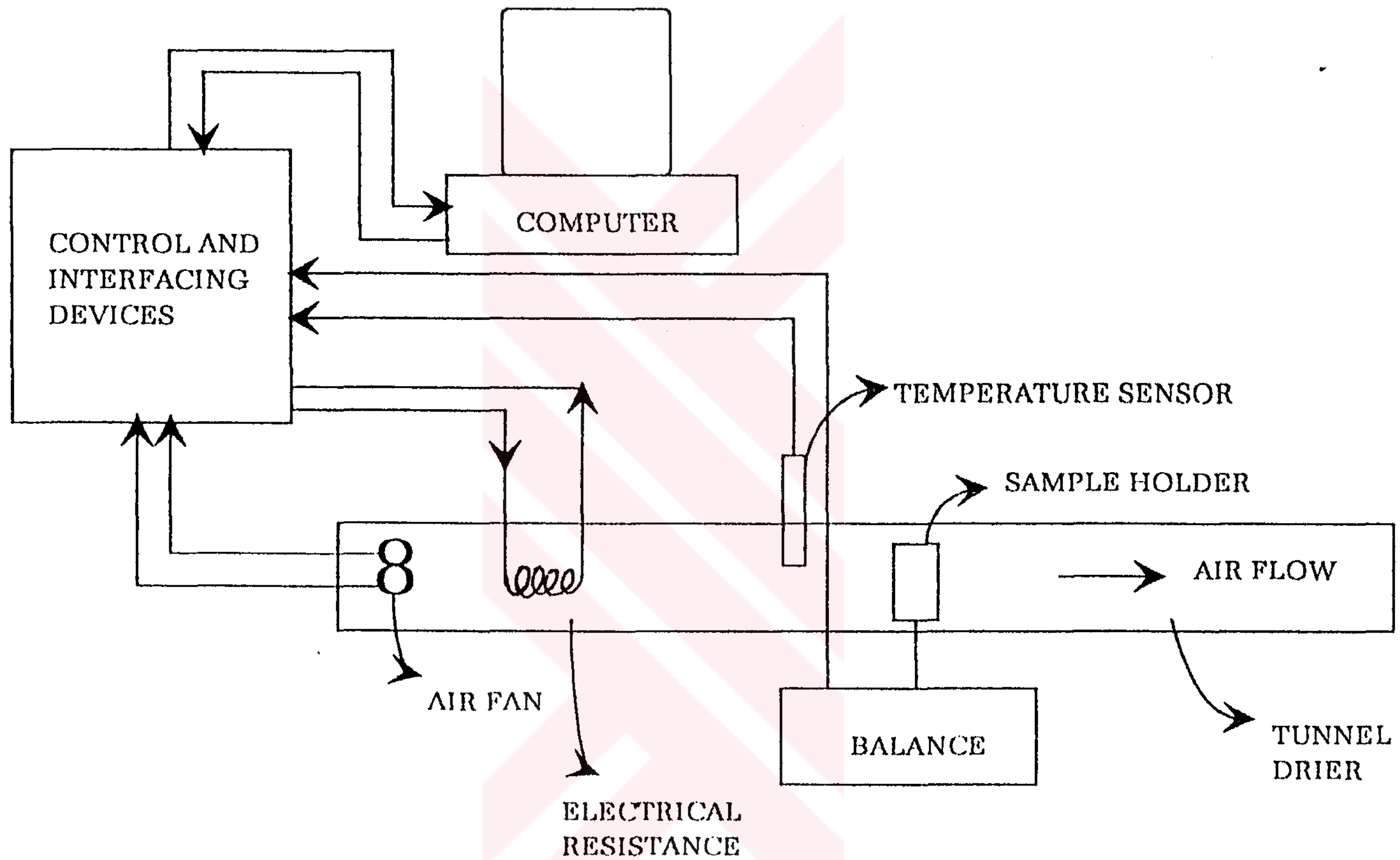

Figure 1. Experimental set-up.

temperature by means of an electrical heater placed into the drying tunnel in front of the air fan.

3.2. The Yeast:

Fresh compressed yeast (CY) preparations were supplied by Pakmaya and fresh CY were used throughout the experiments.

3.3. Preparation of the Samples:

Experiments were done with commercial compressed yeast (Pakmaya, Turkey). It was converted into a paste by disintegrating the particles. About 2 mm thick paste was wrapped into cheese cloth and placed into the sample holder connected to the scale with the largest surface area perpendicular to the air flow.

3.4. Enumeration of the Microbial Growth:

Viable microbial counts were performed with surface spreading on 2% bacteriological agar (Oxoid, England), 2% glucose (Merck, Germany), 0.5% yeast extract (Oxoid, England), 0.1% peptone (Oxoid, England) containing media (Appendix B). Decimal dilutions were made with 0.9% sodium chloride solution in tubes. Three replications were performed for each experimental run for the dilutions which were given the optimum number of colony for counting after 36 hours at 32 °C.

3.5. Sterilization:

The agar media and tubes with sodium chloride solution for serial dilutions were sterilized in an autoclave at 121 °C for 15 minutes under 1.1. atm.

All other glassware were sterilized by dry heat in an incubator at 180 °C for 2 hours.

CHAPTER III

RESULTS AND DISCUSSION

The aim of this study was to determine the drying and death rates of baker's yeast in a computer controlled laboratory scale tunnel dryer with varying air velocity and temperatures within the range of and 2.0-3.0 m/s and 40-60 °C.

Experiments were done with the commercial compressed yeast wrapped into cheese cloth. The cheese cloth was thin and had large holes and it did not affect the heat and mass transfer rates from the air to the yeast paste. The thickness and shape of the paste were almost the same, therefore was not considered as a parameter in the experiments. Percentage of the dry solids obtained after the drying experiments are given in Table A4, Table A5, and Table A6. The percentage of dry solids obtained after the experiments were low with low air temperatures. Increasing the air temperature increased the final percentage of the attained dry solids regardless of the air velocity. There is about 8 % moisture in the commercial active dry yeast, therefore the moisture content of the dry product obtained in this study at higher drying temperatures was in the same range of that of the commercial preparations. The death and drying rates of the yeast are affected by the confidential additives and technology used to produce the compressed yeast. In the commercial applications more temperature resistant strains are used for active dry yeast production than the compressed yeast strains

(Reed and Nagodawithana, 1991). A typical commercial compressed yeast preparation was used in this study, therefore higher viability may be expected than those reported here when the studies are repeated with the commercially prepared active dry yeast strains.

4.1. Drying Model:

Drying of porous solids may exhibit two stages: A constant rate period followed by a falling rate period. However, in this study a constant rate period was not observed whereas two falling rate periods were present. No constant rate period and two falling rate periods were also obtained for Topioca slices (Chirife and Cachero, 1970), for sugar beet slices (Vaccarezza et al., 1974), sweet potato slices (Diamente and Munro, 1991), and for salted fish (Del Valle and Nickerson, 1968).

The rate of drying during the falling rate period is directly proportional to the difference between the actual moisture content of the material and the equilibrium moisture content which is determined by the sorption isotherm of the material (Lewis, 1921). Weight loss in the first falling rate period was modeled as:

$$\frac{dw}{dt} = - k_w (w-w^*) \qquad (1)$$

where w is the dimensionless weight calculated by dividing the weight of the slices at time t to its initial weight at the beginning of an experiment. w^* is the lowest attainable value of w when moisture contents of the dry yeast comes in equilibrium with that of ambient air. k_w is a weight loss constant evaluated with linear regression from the experimental data by using the integrated form of the

Equation 1. The experimental data for w* is given in Table A7. A similar expression was recently suggested while studying drying behavior of apple slices in the same experimental set-up (Özilgen et al., 1995). Values of w* were between 0.37 and 0.47 (dimensionless). Agreement of the model with the experimental data is exemplified with an arbitrarily chosen typical set of data in Figure 2.

The fresh compressed yeast pellets were dried for 45, 60, 90, 120, 150, and 180 minutes under constant experimental conditions. The weight loss constant k_w was evaluated in each of these experiments separately and its mean value was used for further analysis. The experimental values of k_w are given in Table A8, Table A9, and Table A10 for air velocities of 2.0, 2.5, and 3.0 m/s respectively. The pooled variance of the weight loss constant k_w was 4.7 x 10^{-3} min^{-1}. Variance of parameter k_w had the same order of magnitude under all of the experimental conditions and its value was not correlated with the duration of the experiments, temperature or velocity of the air.

An Arrhenius type expression was used to model the temperature effects on parameter k_w :

$$k_w = k_{wo} \exp \left[\frac{-E_{aw}}{RT}\right] \qquad (2)$$

Constants k_{wo} and E_{aw} were evaluated with the typical Arrhenius plots after taking logarithm of Equation 2 as exemplified with typical sets of data in Figure 3. The corresponding experimental data is given in Table A11.

Values of constants k_{wo} and E_{aw} were found to be dependent on the air flow rates as depicted in Figure 4. The data of Figure 4 is given in Table A12.

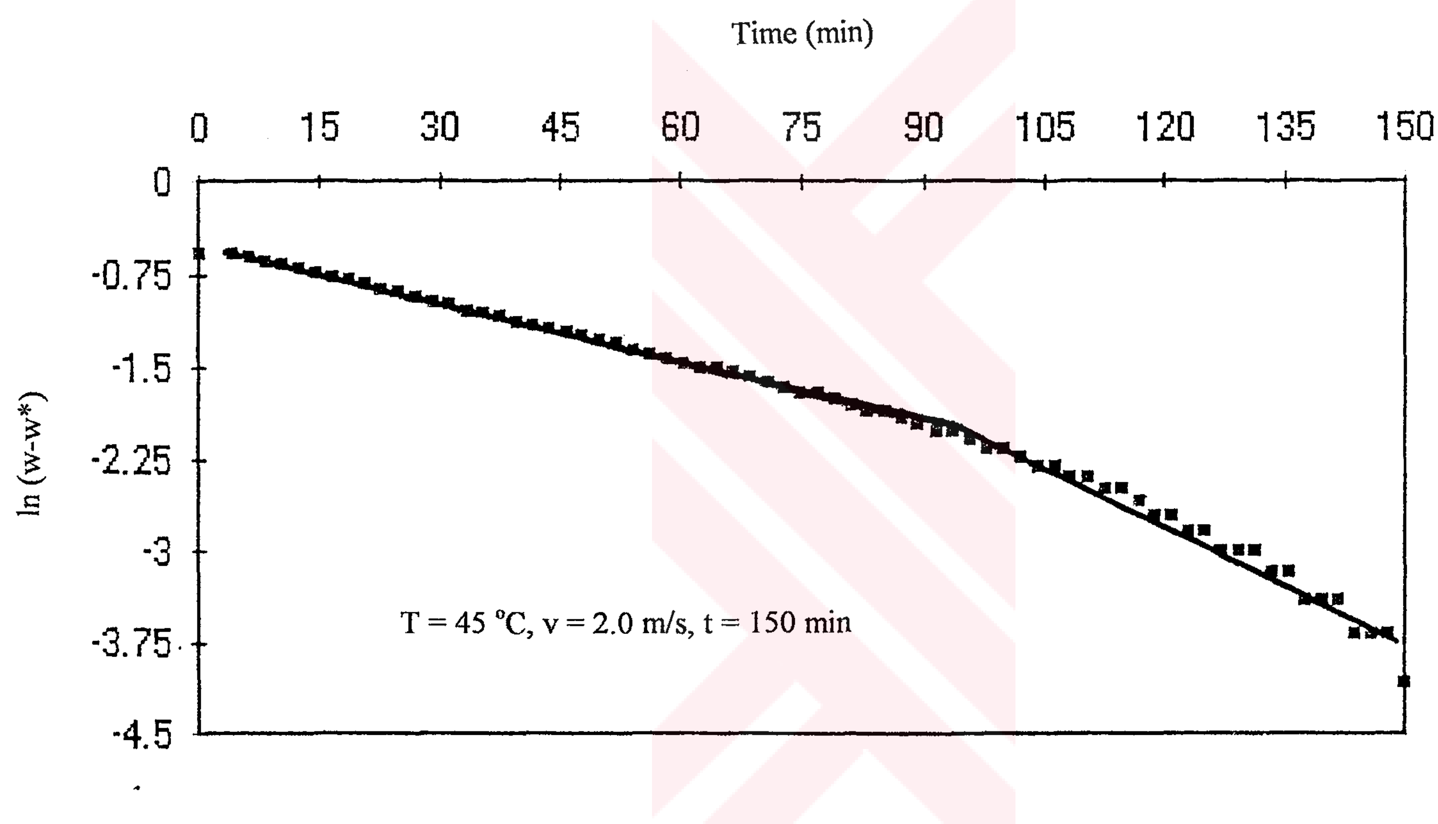

Figure 2. Comparison of the drying model (——) with a typical set of experimental data (■).

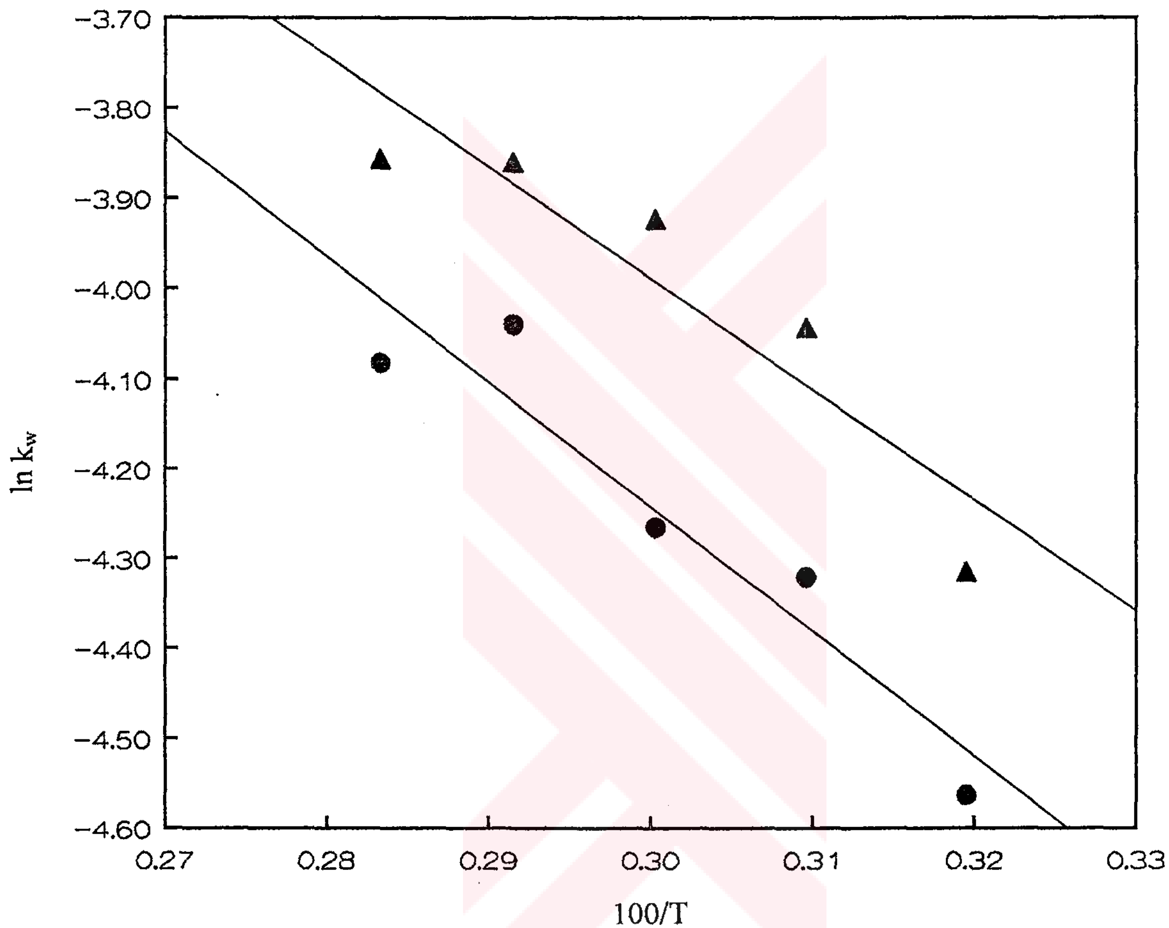

Figure 3. Arrhenius plots for evaluation of constants k_{wo} and E_{aw}. Experimental data were shown in symbols with (▲) 2.0 m/s and (●) 2.5 m/s of air velocity. The solid lines are the best fitting lines.

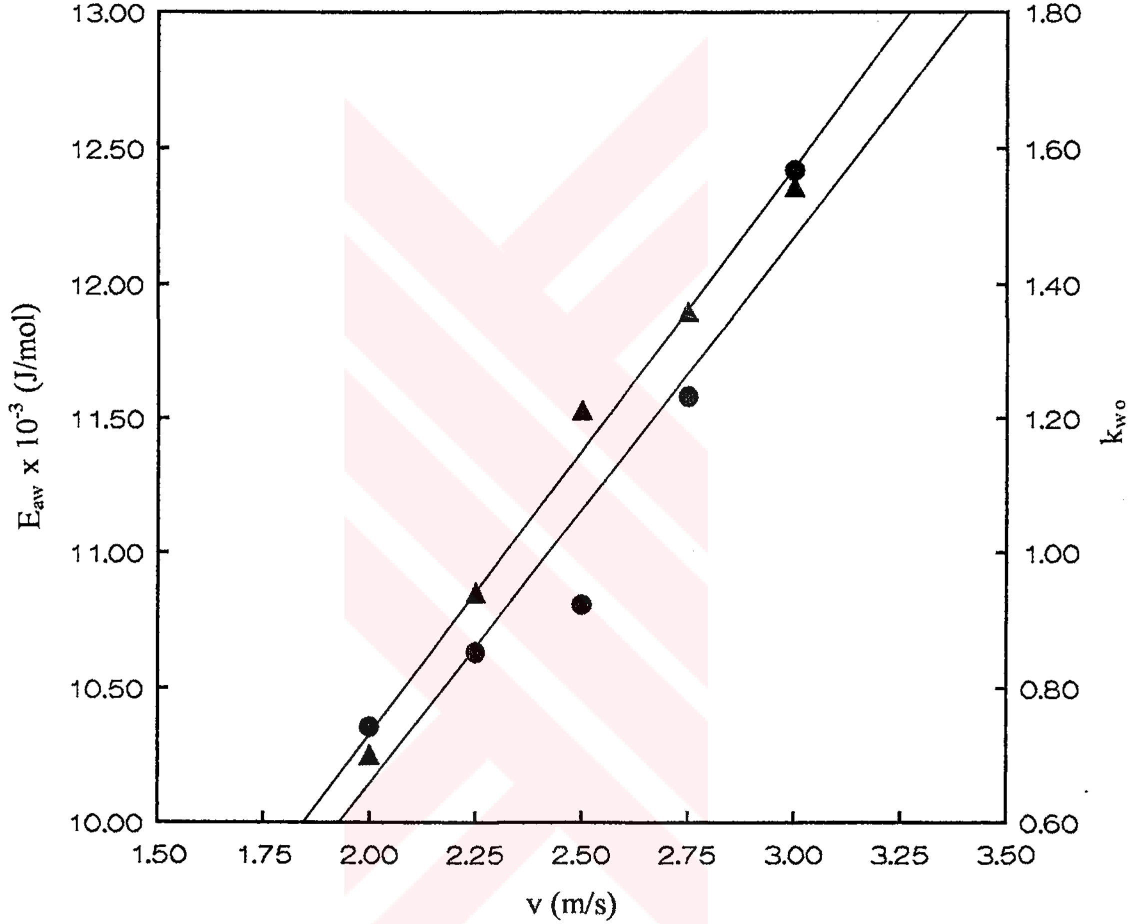

Figure 4. Variation of activation energy E_{aw} (▲), and pre-exponential constant k_{wo} (●) with velocity of air. Equations of the best fitting lines (——) are : $E_{aw} = 2.1 \times 10^3 v + 6.1 \times 10^3$ (r = 0.99), $k_{wo} = 0.81 v - 0.97$ (r = 0.96) where v is the velocity of air expressed in m/s.

During the second falling rate period water is removed from the surface, subsequently the dry zones enlarge in expense of the wet regions. Heat and mass transfer rate constants and consequently parameter k_{wo} increase with the velocity of air.

Constants of the Arrhenius type expressions are generally interrelated. Under slightly different experimental conditions any change in parameter k_{wo} may be compensated by the changes in E_{aw} :

$$\ln k_{wo} = \alpha E_{aw} + \beta \qquad (3)$$

Equation 3 is referred to as a compensation relation. Although parameters k_{wo} and E_{aw} changes with the experimental conditions, parameters α and β are constants. Equation 3 and its derivatives are generally observed with various physical, chemical and biological reactions and may be used in process design. Review of the literature and description of the use of the compensation relations in process design is described in detail by Özilgen and Özilgen (1995). The compensation relation was not obtained previously with the drying rate constants, therefore Equation 3 is new to the literature. Comparison of Equation 3 with the experimental data is depicted in Figure 5, experimental values are given in Table A13.

A kink was observed about 75-110 minutes after the beginning of the drying process depending on the experimental conditions as exemplified in Figure 2. The second region of the plot observed at the later stages of the experiments was attributed to the second falling rate period of the drying process. Drying rate constant referring to the second falling rate period was denoted as k_{w2} , and its mean value and variance were 4.3×10^{-2} min^{-1} and 9.8×10^{-3} min^{-1} , respectively.

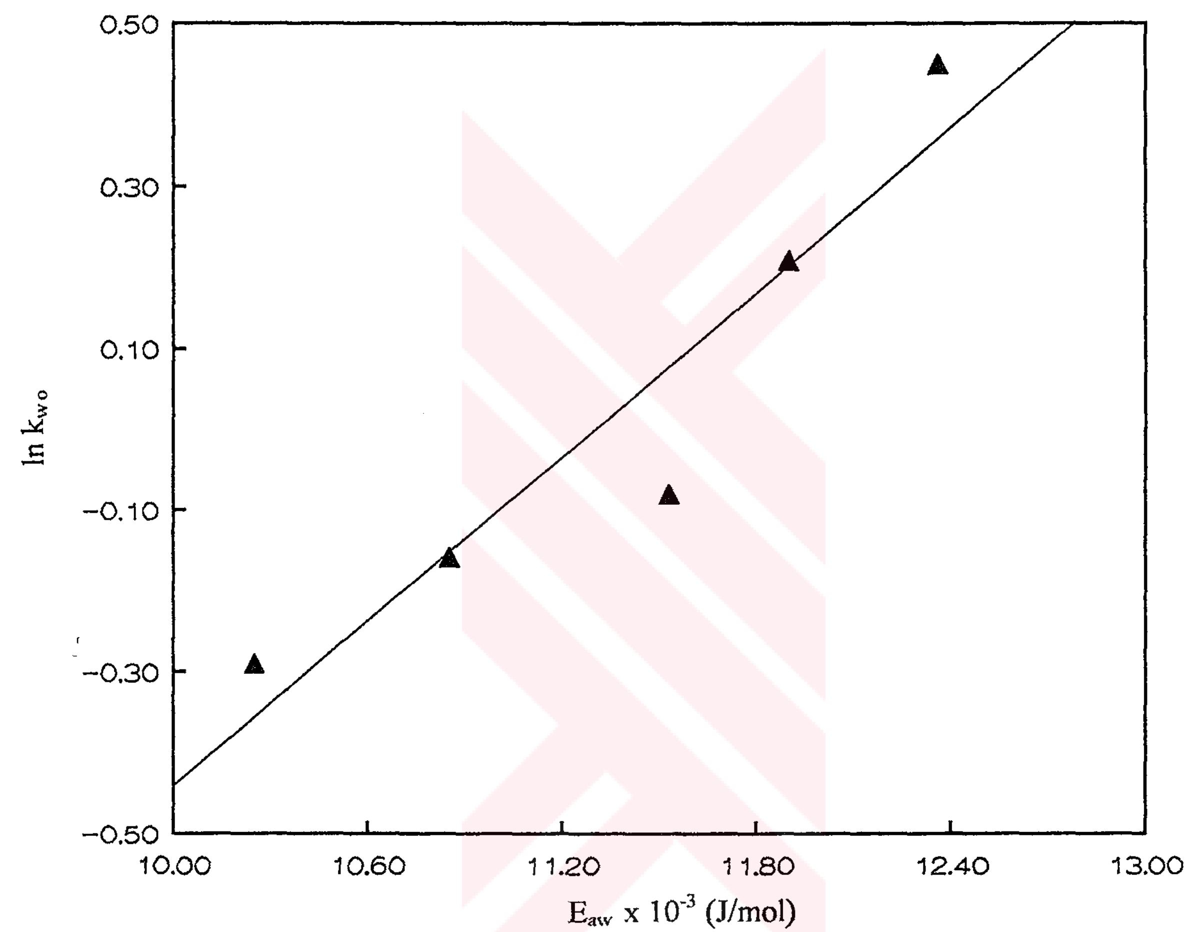

Figure 5. Compensation relation for the Arrhenius expression parameters of the first falling rate drying constant k_w. Experimental data are shown in symbols (▲). Equation of the best fitting line (——) is: $\ln k_{wo} = 3.38 \times 10^{-4} E_{aw} - 3.82$ (r = 0.95).

There was no clear-cut transition between the falling rate periods, therefore the distinction was made intuitively to obtain the highest correlation coefficients while evaluating the constants k_w and k_{w2}. The experimental values of k_{w2} is given in Table A14. The second falling rate period is essentially a diffusion rate controlled process, therefore parameter k_{w2} was not affected by the air velocity. Similarly, air velocity did not affect the drying rate during the falling rate period in potato chips (Ede, 1958), in beans and white beans (Hutchinson and Otten, 1983), in fruits and vegetables (Saravacos and Charm, 1962), and in French fried potatoes (Chiang and Petersen, 1985). Parameter k_{w2} was not affected by the air temperature and the duration of the experiments. Having no affect of temperature on k_{w2} may indicate that the diffusion constant of water in the yeast cells did not change much with temperature within the range of the experiments.

4.2. Microbial Death Model:

The initial objective of experimental kinetic studies was the development of a mathematical model to describe the reaction rate as a function of experimental variables (Charles and Richard, 1980). Little information is available in the literature concerning the affect of various drying conditions on the functional characteristics of the resulting dry protein (Labuza et al., 1972).

Data for the survival kinetics of the microorganisms were obtained during the same experiments with weight loss. Death rate of the microorganisms were described as:

$$\frac{dx}{dt} = - k_d\, x \qquad (4)$$

The experimental values of the microbial counts are given in Table A15, Table A16, and Table A17 for air velocities of 2.0, 2.5, and 3.0 m/s respectively. Average initial microbial counts of the compressed yeast was 3.6×10^{10} cfu /g dry yeast with a standard deviation of 5.0×10^{9} cfu / g dry yeast. Initial percentage of the dry solids in the compressed yeast were about 35 %. Integrated form of Equation 4 was used to determine the death rate constant k_d , and the corresponding experimental values of k_d are given in Table A18. Temperature affects on the death rate constant was described with the Arrhenius expression:

$$k_d = k_{do} \exp \left[\frac{-E_{ad}}{RT} \right] \qquad (5)$$

Arrhenius plots for the death rate constant k_d are depicted in Figure 6, corresponding experimental data is given in Table A19. Elizondo and Labuza (1974), reported a kink in the Arrhenius plot at around 84 °C while studying the death of *Saccharomyces cerevisiae* in a spray dryer. Temperature range of the present study is lower than that of Elizondo and Labuza (1974), also the drying medium, technology and yeast were different, therefore a kink was not observed in the Arrhenius plot. Effect of the air flow rate on parameters k_{do} and E_{ad} are shown in Figure 7. The compensation relation between these parameters is shown as:

$$\ln k_{do} = \delta E_{ad} + \phi \qquad (6)$$

where parameters δ and ϕ are constants. Comparison of equation 6 with the experimental data is depicted in Figure 8. The corresponding experimental data for Figure 7 and Figure 8 are given in Table A20 and Table A21 respectively.

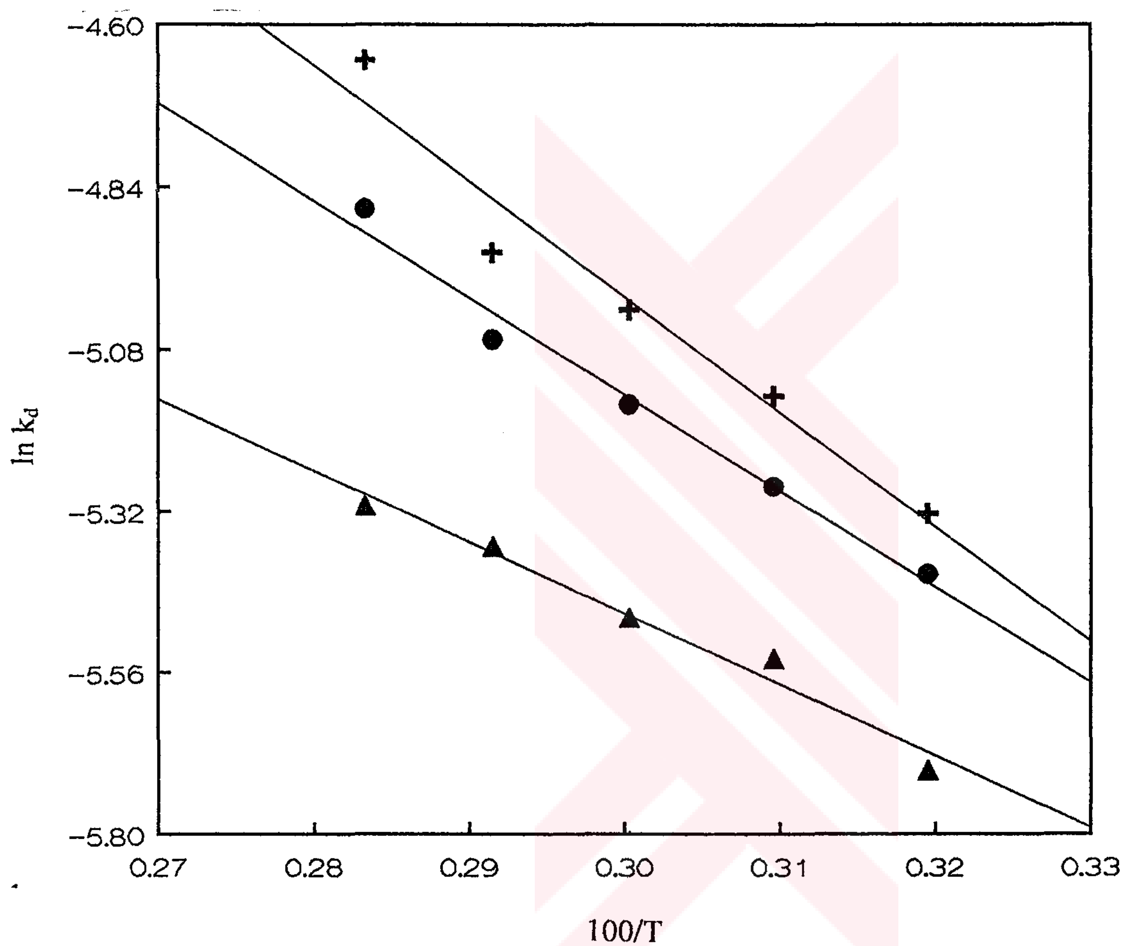

Figure 6. Arrhenius plots for evaluation of constants k_{do} and E_{ad} . Experimental data were shown in symbols with (▲) 2.0 m/s, (●) 2.5 m/s, and (+) 3.0 m/s of air velocity. The solid lines are the best fitting lines.

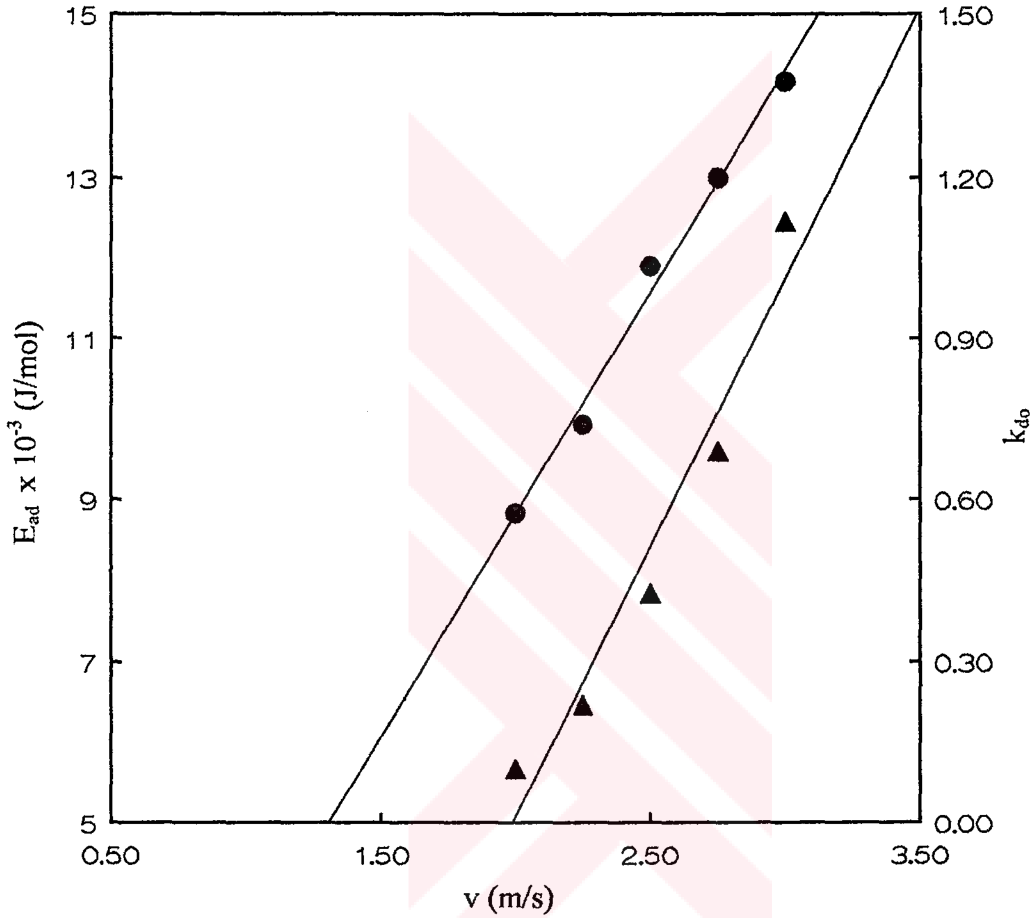

Figure 7. Variation of activation energy E_{ad} (●) and pre-exponential constant k_{do} (▲) with velocity of air. Equations of the best fitting lines(——) are: $E_{ad} = 5.5 \times 10^3 \, v + 2.2 \times 10^3$ ($r = 0.99$), $k_{do} = v - 2.0$ ($r = 0.97$) where v is the velocity of air expressed in m/s.

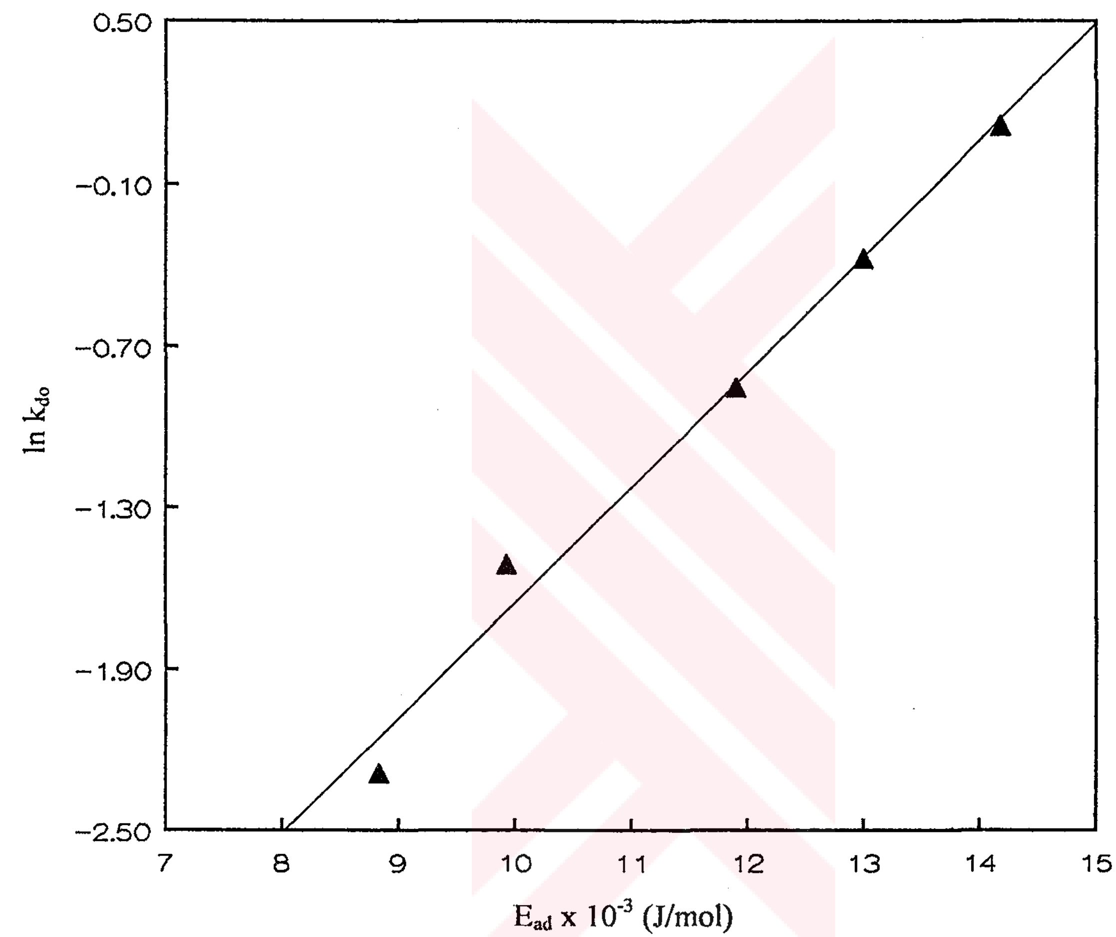

Figure 8. Compensation relation for the Arrhenius expression parameters of the death rate constant k_d. Experimental data are shown in symbols (▲). Equation of the best fitting line (——) is: $\ln k_{do} = 4.3\times10^{-4} E_{ad} - 5.94$ ($r = 0.99$).

Kinetic compensation relations for the constants of the Arrhenius expression of the microbial death constant has been suggested in the previous studies as reviewed by Özilgen and Özilgen (1995).

4.3. Relation Between Drying and Microbial Death:

Since, the same mathematical models (with different parameter values) described the affects of air velocity and temperature on the microbial death and first falling rate drying constants, a correlation between these two sets of constants was sought. Two linear correlations were observed as depicted in Figure 9a and Figure 9b , the experimental values are given in Table A22 and Table A23 respectively. The first relation was valid at 2.0 m/s of air velocity and the second relation was valid at 2.5 and 3.0 m/s of air velocities. Figure 9 implies that, microbial death was slower at low air velocity.

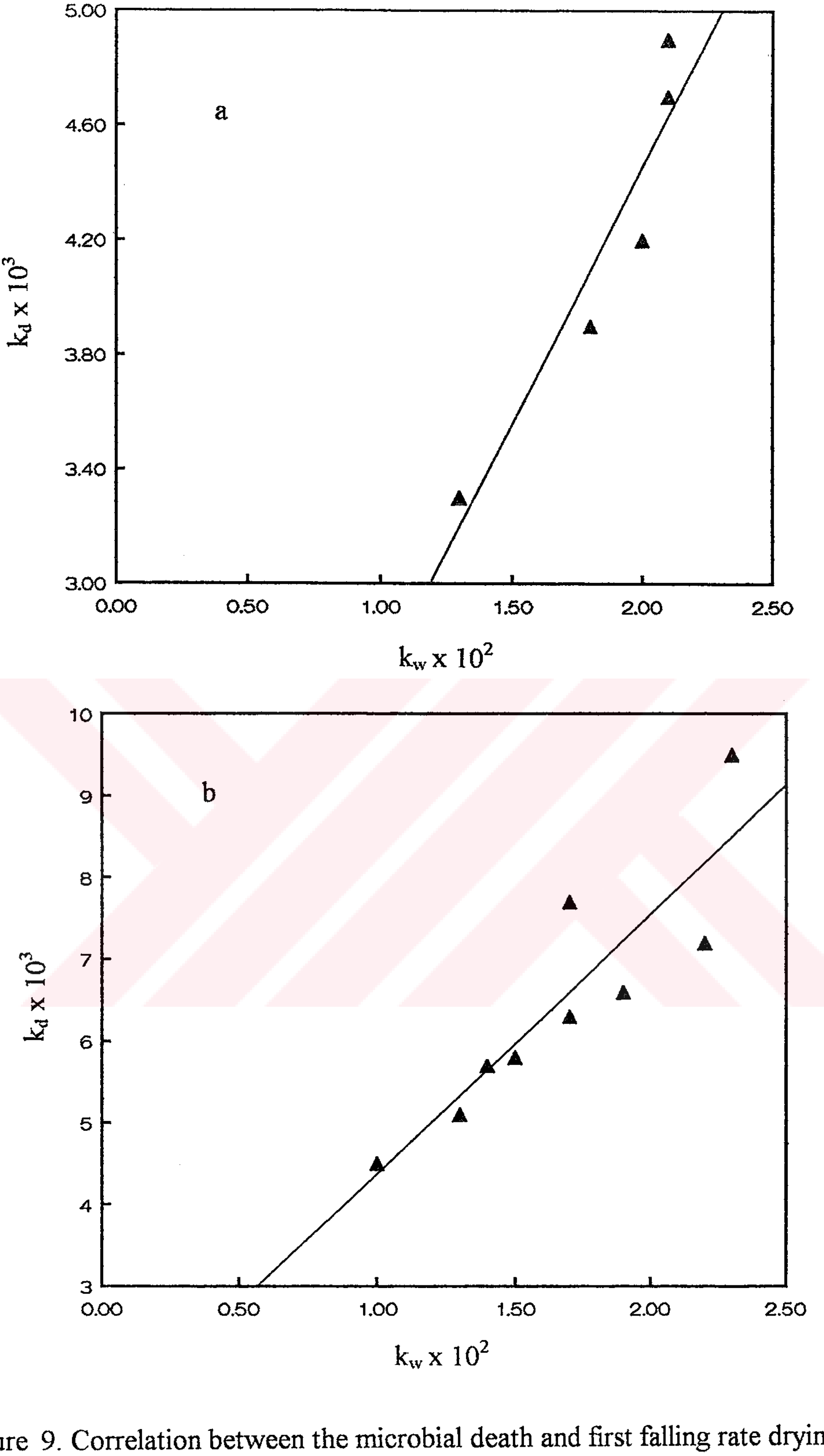

Figure 9. Correlation between the microbial death and first falling rate drying constants: (▲) experimental data, (——) best fitting lines. (a) v = 2.0 m/s; $k_d = 8.4 \times 10^{-4} + 0.179\, k_w$ (r = 0.94), (b) v = 2.5 and 3.0 m/s; $k_d = 1.2 \times 10^{-3} + 0.317\, k_w$ (r = 0.89).

CHAPTER IV

CONCLUSIONS

Mathematical models of the first falling rate and microbial death were similar, implying that the physical factors affected both phenomena the same way.

It was also shown that the death and first falling rate constants were related. Drying air velocity had no affect on the second falling rate constant.

The death rate constants were smaller at the slower air flow rates.

RECOMMENDATIONS

In this study, drying and death rates of baker's yeast were studied in a computer controlled laboratory scale tunnel dryer with varying air velocity and temperatures within the range of 40 - 60 °C and 2.0 - 3.0 m/s under constant drying conditions. This study may be performed by using different temperatures lower than 40 °C and air velocities higher than 3.0 m/s with varying temperature profiles.

The activity of the dried yeast may be measured by the CO_2 production of the dough produced.

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APPENDIX A

EXPERIMENTAL AND CALCULATED DATA OF COMPRESSED YEAST

Table A1 Randomly selected experimental periods and temperatures for additional runs

v=2.25 m/s

T (°C)	t (min)
40	120
45	150
50	60
55	45
60	90

v=2.75 m/s

T (°C)	t (min)
40	90
45	120
50	120
55	150
60	60

Table A2 Experimental constants of parameters for drying model

v=2.25 m/s

Trials	E_{aw} (J/g.mol)	k_{wo} (min^{-1})	sum (di^2)
1	11500	1.0716	2.8129
2	11100	0.9312	2.8116
3	10960	0.8866	2.8117
4	10853	0.8538	2.8119
5	**10852**	**0.8538**	**2.8103**
6	10851	0.8532	2.812
7	10800	0.8381	2.8126
8	10450	0.7412	2.8136
9	10000	0.6329	2.8183
10	9000	0.4455	2.8373

v=2.75 m/s

Trials	E_{aw} (J/g.mol)	k_{wo} (min^{-1})	sum (di^2)
1	12000	1.444	1.4002
2	11925	1.244	1.4054
3	11902	1.234	1.4069
4	11900	1.233	1.4068
5	**11898**	**1.2323**	**1.4067**
6	11896	1.231	1.4073
7	11880	1.2245	1.4083

Table A3 Experimental constants of parameters for microbiological model

v=2.25 m/s

Trials	E_{ad} (J/g.mol)	k_{do} (min^{-1})	sum (di^2*exp3)
1	10500	0.3085	9.3
2	10222	0.2662	5.28
3	10111	0.2492	3.82
4	10000	0.2323	2.81
5	9950	0.2247	2.56
6	9930	0.2216	2.54
7	**9927**	**0.2212**	**2.45**
8	9925	0.2209	2.51
9	9917	0.2198	2.48
10	9908	0.2184	2.51
11	9890	0.2156	2.54
12	9800	0.2018	3.24

v=2.75 m/s

Trials	E_{ad} (J/g.mol)	k_{do} (min^{-1})	sum (di^2*exp3)
1	12400	0.598	5.21
2	12450	0.6056	4.73
3	12550	0.6208	3.77
4	12600	0.6285	3.42
5	12900	0.6742	1.93
6	12973	0.6853	1.89
7	**12999**	**0.6894**	**1.85**
8	13002	0.6901	1.86
9	13033	0.6944	1.94
10	13100	0.6894	1.98

Table A4 Experimental percentage of the dry solids for commercial compressed yeast after drying at v= 2.0 m/s

T (°C)	t (min)	% dry solid
	45	47.52
	60	48.16
40	90	53.84
	120	66.43
	150	68.92
	180	83.66
	45	48.45
	60	49.02
45	90	63.07
	120	63.94
	150	76.43
	180	79.41
	45	47.45
	60	51.93
50	90	63.01
	120	69.48
	150	72.89
	180	76.55
	45	59.15
	60	53.41
55	90	79.41
	120	75.91
	150	87.21
	180	93.58
	45	54.41
	60	66.32
60	90	74.82
	120	77.59
	150	83.02
	180	96.46

Table A5 Experimental percentage of the dry solids for commercial compressed yeast after drying at v= 2.5 m/s

T (°C)	t (min)	% dry solid
	45	37.6
	60	44.7
40	90	45.6
	120	64.1
	150	68.2
	180	80.88
	45	43.4
	60	44.7
45	90	47.8
	120	75.93
	150	76.33
	180	86.02
	45	48.7
	60	49.6
50	90	64.3
	120	70.4
	150	76.82
	180	89.75
	45	51.4
	60	52.29
55	90	53.98
	120	78.81
	150	89.17
	180	92.85
	45	47.88
	60	58.3
60	90	70.94
	120	69.48
	150	84.78
	180	92.64

Table A6 Experimental percentage of the dry solids for commercial compressed yeast after drying at v= 3.0 m/s

T (°C)	t (min)	% dry solid
	45	51.26
	60	52.62
40	90	66.17
	120	69.48
	150	78.9
	180	80.62
	45	46.08
	60	51.52
45	90	70.74
	120	71.89
	150	80.6
	180	87.38
	45	46.21
	60	52.5
50	90	69.48
	120	75.36
	150	75.52
	180	82.8
	45	59.11
	60	48.98
55	90	57.1
	120	74.78
	150	66.99
	180	73.82
	45	49.12
	60	61.56
60	90	75.52
	120	87.87
	150	90.04
	180	88.43

Table A7 Experimental data for w* (dimensionless)

v (m/s)	T (°C)	w*
	40	0.41525
	45	0.43750
2.0	50	0.45378
	55	0.37121
	60	0.36029
	40	0.42953
	45	0.40384
2.5	50	0.38709
	55	0.37415
	60	0.3750
	40	0.43089
	45	0.39716
3.0	50	0.41958
	55	0.46451
	60	0.38582

Table A8 Experimental values of k_w (min^{-1}) at v= 2.0 m/s

T (°C)	t (min)	k_w (min^{-1})	r	$k_{w\ mean}$
	45	0.01489	0.9962	
	60	0.01137	0.9986	
40	90	0.01068	0.9992	0.01352
	120	0.01413	0.9965	
	150	0.01246	0.9982	
	180	0.01668	0.9964	
	45	0.0163	0.9911	
	60	0.01315	0.9974	
45	90	0.01784	0.9976	0.01755
	120	0.01431	0.9947	
	150	0.01578	0.9981	
	180	0.02792	0.9661	
	45	0.01563	0.9906	
	60	0.01631	0.9914	
50	90	0.0196	0.9900	0.01979
	120	0.02097	0.9924	
	150	0.01993	0.9854	
	180	0.02628	0.9914	
	45	0.02567	0.9972	
	60	0.01432	0.9947	
55	90	0.02553	0.9962	0.02107
	120	0.01781	0.9954	
	150	0.02299	0.9984	
	180	0.02007	0.9981	
	45	0.01989	0.9964	
	60	0.02447	0.9986	
60	90	0.0211	0.9969	0.02114
	120	0.01751	0.9991	
	150	0.01611	0.0991	
	180	0.02775	0.997	

Table A9 Experimental values of k_w (min^{-1}) at v= 2.5 m/s

T (°C)	t (min)	k_w (min^{-1})	r	$k_{w\ mean}$
	45	0.00326	0.9940	
	60	0.00878	0.9960	
40	90	0.00622	0.9990	0.01043
	120	0.01406	0.9966	
	150	0.01305	0.9947	
	180	0.0172	0.9983	
	45	0.01	0.9973	
	60	0.00841	0.9976	
45	90	0.00717	0.9962	0.01329
	120	0.01989	0.9939	
	150	0.01635	0.9981	
	180	0.0179	0.9962	
	45	0.01314	0.998	
	60	0.01192	0.9973	
50	90	0.01141	0.9991	0.01405
	120	0.01495	0.9943	
	150	0.01511	0.9968	
	180	0.01775	0.9956	
	45	0.01758	0.9871	
	60	0.01356	0.993	
55	90	0.0098	0.9941	0.01761
	120	0.01942	0.9956	
	150	0.02428	0.9821	
	180	0.021	0.9951	
	45	0.01384	0.997	
	60	0.0184	0.996	
60	90	0.01917	0.9994	0.01688
	120	0.01384	0.9979	
	150	0.0188	0.9911	
	180	0.0172	0.989	

Table A10 Experimental values of k_w (min^{-1}) at v= 3.0 m/s

T (°C)	t (min)	k_w (min^{-1})	r	$k_{w\ mean}$
	45	0.01959	0.9980	
	60	0.0162	0.9980	
40	90	0.01998	0.9970	0.01926
	120	0.01745	0.9977	
	150	0.0231	0.9750	
	180	0.01924	0.9973	
	45	0.013	0.9958	
	60	0.01414	0.9983	
45	90	0.02091	0.9990	0.0150
	120	0.01318	0.9960	
	150	0.01427	0.9900	
	180	0.014	0.9977	
	45	0.021	0.9971	
	60	0.0101	0.9968	
50	90	0.022	0.9985	0.01893
	120	0.02197	0.9884	
	150	0.0245	0.9980	
	180	0.014	0.9800	
	45	0.03475	0.9900	
	60	0.0144	0.9930	
55	90	0.01456	0.9920	0.02181
	120	0.02351	0.9920	
	150	0.0235	0.9920	
	180	0.02011	0.9986	
	45	0.01524	0.9933	
	60	0.0222	0.9960	
60	90	0.02371	0.9972	0.0220
	120	0.02332	0.9950	
	150	0.02553	0.9980	
	180	0.022	0.9980	

Table A11 Experimental data for Arrhenius plots for evaluation of constants k_{wo} (min^{-1}) and E_{aw} (J/g.mol)

Drying air velocity (m/s)	100/T(K)	ln k_w
	0.3195	-4.31489
	0.3096	-4.04271
2.0	0.3003	-3.92273
	0.2915	-3.86014
	0.2833	-3.85783
	0.3195	-4.56326
	0.3096	-4.32097
2.5	0.3003	-4.26535
	0.2915	-4.07061
	0.2833	-4.08162

Table A12 Experimental data for variation of E_{aw} (J/g.mol) and k_{wo} (min^{-1}) with velocity of drying air

Drying air velocity (m/s)	E_{aw} (J/g.mol)	k_{wo} (min^{-1})
2.0	10250	0.7425
2.25	10852	0.8538
2.5	11529	0.9231
2.75	11898	1.2323
3.0	12357	1.5680

Table A13 Experimental data for compensation relation for the Arrhenius expression parameters of the first falling rate drying constant k_w (min^{-1})

Drying air velocity (m/s)	ln k_{wo} (min^{-1})	E_{aw}
2.0	-0.2978	10250
2.25	-0.1583	10852
2.5	-0.08	11529
2.75	0.2089	11898
3.0	0.4498	12357

Table A14 Experimental values of k_{w2} (min^{-1})

Drying air velocity (m/s)	T (°C)	t (min)	k_{w2} (min^{-1})	r
	40	180	0.03520	0.95
2.0	45	150	0.03211	0.97
	55	150	0.04714	0.95
	40	180	0.04137	0.94
	45	180	0.044	0.95
2.5	50	180	0.04204	0.95
	55	180	0.04686	0.96
	60	180	0.042	0.96
	40	180	0.0344	0.95
	45	180	0.043	0.94
	50	180	0.0506	0.96
3.0	55	120	0.066	0.91
	55	180	0.029	0.89
	60	120	0.054	0.94
	60	150	0.045	0.96
	60	180	0.028	0.95

Table A15 Experimental values of microbial counts for v= 2.0 m/s

T (°C)	t (min)	X_f (exp^{-10})	X_f/X_o
	45	3.021	0.91
	60	2.888	0.87
40	90	2.656	0.80
	120	2.49	0.75
	150	2.191	0.66
	180	1.892	0.57
	45	3.753	0.90
	60	3.253	0.78
45	90	3.002	0.72
	120	2.919	0.70
	150	2.502	0.60
	180	2.043	0.49
	45	2.955	0.89
	60	2.49	0.75
50	90	2.357	0.71
	120	2.291	0.69
	150	1.926	0.58
	180	1.527	0.46
	45	3.211	0.77
	60	3.002	0.72
55	90	2.252	0.54
	120	2.002	0.48
	150	1.918	0.46
	180	1.793	0.43
	45	3.002	0.72
	60	2.961	0.71
60	90	2.168	0.52
	120	1.918	0.46
	150	1.71	0.41
	180	1.626	0.39

Table A16 Experimental values of microbial counts for v= 2.5 m/s

T (°C)	t (min)	X_f (exp^{-10})	X_f/X_o
	45	6.201	0.9
	60	5.788	0.84
40	90	5.099	0.74
	120	4.41	0.64
	150	3.927	0.57
	180	3.376	0.49
	45	5.925	0.86
	60	5.443	0.79
45	90	4.41	0.64
	120	4.134	0.6
	150	3.514	0.51
	180	2.894	0.42
	45	5.512	0.8
	60	4.892	0.71
50	90	4.134	0.6
	120	3.721	0.54
	150	3.101	0.45
	180	2.412	0.35
	45	3.583	0.52
	60	3.238	0.47
55	90	2.687	0.39
	120	2.205	0.32
	150	1.86	0.27
	180	1.516	0.22
	45	3.307	0.48
	60	2.963	0.43
60	90	2.412	0.35
	120	1.86	0.27
	150	1.516	0.22
	180	1.171	0.17

Table A17 Experimental values of microbial counts for v= 3.0 m/s

T (°C)	t (min)	X_f (exp^{-10})	X_f/X_o
	45	3.203	0.88
	60	2.948	0.81
40	90	2.73	0.75
	120	2.293	0.63
	150	1.966	0.54
	180	1.638	0.45
	45	2.985	0.82
	60	2.912	0.80
45	90	1.966	0.54
	120	1.893	0.52
	150	1.674	0.46
	180	1.347	0.40
	45	2.402	0.66
	60	1.966	0.54
50	90	1.638	0.45
	120	1.565	0.43
	150	1.165	0.32
	180	0.91	0.25
	45	1.107	0.45
	60	0.984	0.40
55	90	0.91	0.37
	120	0.64	0.26
	150	0.037	0.015
	180	0.081	0.033
	45	0.664	0.20
	60	0.498	0.15
60	90	0.398	0.12
	120	0.299	0.09
	150	0.232	0.07
	180	0.199	0.06

Table A18 Experimental values of k_d (min^{-1})

Drying air velocity (m/s)	T (°C)	k_d (min^{-1})	r
	40	0.00333	0.98
	45	0.00393	0.94
2.0	50	0.00418	0.92
	55	0.00465	0.88
	60	0.00494	0.94
	40	0.00446	0.99
	45	0.00508	0.99
2.5	50	0.00574	0.99
	55	0.00632	0.99
	60	0.00766	0.99
	40	0.00488	0.99
	45	0.00581	0.94
3.0	50	0.0066	0.97
	55	0.00718	0.88
	60	0.00953	0.98

Table A19 Experimental data for Arrhenius plots for evaluation of constants k_{do} (min^{-1}) and E_{ad} (J/g.mol)

Drying air velocity (m/s)	100/T(K)	ln k_d
	0.3195	-5.70478
	0.3096	-5.53912
2.0	0.3003	-5.47744
	0.2915	-5.37089
	0.2833	-5.31039
	0.3195	-5.41261
	0.3096	-5.28244
2.5	0.3003	-5.16030
	0.2915	-4.87174
	0.2833	
	0.3195	-5.32261
	0.3096	-5.14817
3.0	0.3003	-5.02069
	0.2915	-4.93646
	0.2833	-4.65331

Table A20 Experimental data for variation of E_{ad} (J/g.mol) and k_{do} (min^{-1}) with velocity of drying air

Drying air velocity (m/s)	E_{ad} (J/g.mol)	k_{do} (min^{-1})
2.0	8831	0.1018
2.25	9927	0.2212
2.5	11899	0.4266
2.75	12999	0.6894
3.0	14173	1.119

Table A21 Experimental data for compensation relation for the Arrhenius expression parameters of the death rate constant k_d (min^{-1})

Drying air velocity (m/s)	ln k_{do} (min^{-1})	E_{ad}
2.0	-2.28494	8831
2.25	-1.50869	9927
2.5	-0.85191	11899
2.75	-0.37193	12999
3.0	0.11244	14173

Table A22 Experimental data for correlation between the microbial death k_d (min^{-1}) and first falling rate drying constant k_w (min^{-1}) for v= 2.0 m/s

T(°C)	k_w (min^{-1})*exp 2	k_d (min^{-1})*exp 3
40	1.3	3.3
45	1.8	3.9
50	2.0	4.2
55	2.1	4.7
60	2.1.	4.9

Table A23 Experimental data for correlation between the microbial death k_d (min^{-1}) and first falling rate drying constant k_w (min^{-1}) for v= 2.5 and 3.0 m/s

Drying air velocity (m/s)	T(°C)	k_w (min^{-1})*exp 2	k_d (min^{-1})*exp 3
	40	1.0	4.5
	45	1.3	5.1
2.5	50	1.4	5.7
	55	1.7	6.3
	60	1.7	7.7
	40	1.9	4.9
	45	1.5	5.8
3.0	50	1.9	6.6
	55	2.2	7.2
	60	2.3	9.5

APPENDIX B

FORMULATION OF GROWTH MEDIUM

For one liter medium;

Agar bacteriological	20.0 g
Glucose	20.0 g
Yeast extract	5.0 g
Peptone	1.0 g

Dissolve ingredients in distilled water by gentle heating. Sterilize at 121 °C for 15 minutes.