REVISTA
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Heat and mass exchanging processes in a refrigerated truck body during multi-drop urban distribution of fresh herbs

Procesos de intercambio de calor y masa en el cuerpo de un camión refrigerado durante la distribución urbana de varias gotas de hierbas frescas

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Abstract

The article presents the results of a study on heat and mass transfer processes in a refrigerated truck body with frequent door openings typical for multi-drop urban distribution, and their effect on microbiological indicators and chemical composition of transported fresh herbs. A refrigerated body with an isothermal body of 11 m3 capacity fixed to Gazelle truck chassis loaded with dill and pars-ley as transport cargo were used in a two-stage experiment. The changes in air parameters (temperature, velocity, relative humidity) in various parts of the body were determined depending on the door opening duration when unload-ing part of the product. The heat gain and the amount of condensate from the intake of outside air through the open door were calculated based on the exper-imental data obtained in an empty truck body, and their effect on microbiologi-cal indicators and the chemical composition of greens was determined based on laboratory data obtained after transportation and storage in a commercial re-frigerator. It was established that the amount of heat entering the body through an open door in 10 minutes is comparable to the heat gain through its insulat-ed walls when the door is closed for two hours. 45% of heat and 70% of mois-ture came into the truck body in the first two minutes of door opening. After the transportation and pre-sale storage with a total duration of 78 hours, a sharp

microbial growth was observed. The number of bacteria increased 5-6 times on parsley, and 3-4 times on dill; besides, parsley and dill showed a 10 fold increase in fungi and yeast on their surface, respectively. Over a similar period of time, the same indicators of fresh herbs not subjected to the transpor-tation and stored in a refrigerator at stable temperature and humidity condi-tions increased only 2 times. It has been shown that fluctuations in tempera-ture and humidity in the truck body also lead to a change in the chemical com-position of greens during further cold storage before sale. The obtained data on heat gain during door opening time must be taken into account when calculat-ing the capacity of the truck refrigeration unit.
Keywords: heat and mass transfer, temperature conditions, green herbs, urban distribution, refrigerated truck, microbiological indicators.

Resumen

El artículo presenta los resultados de un estudio sobre los procesos de transferencia de calor y masa en un camión refrigerado con aberturas de puerta frecuentes típicas para la distribución urbana de múltiples gotas, y su efecto sobre los indicadores microbiológicos y la composición química de las hierbas frescas transportadas. En un experimento de dos etapas se utilizó un cuerpo refrigerado con un cuerpo isotérmico de 11 m3 de capacidad fijado al chasis del camión Gazelle cargado con eneldo y perejil como carga de transporte. Los cambios en los parámetros del aire (temperatura, velocidad, humedad relativa) en varias partes del cuerpo se determinaron en función de la duración de la apertura de la puerta al descargar parte del producto. La ganancia de calor y la cantidad de condensado de la entrada de aire exterior a través de la puerta abierta se calcularon en base a los datos experimentales obtenidos en un cuerpo de camión vacío, y se determinó su efecto sobre los indicadores microbiológicos y la composición química de los verdes. basado en datos de laboratorio obtenidos después del transporte y almacenamiento en un refrigerador comercial. Se estableció que la cantidad de calor que ingresa al cuerpo a través de una puerta abierta en 10 minutos es comparable a la ganancia de calor a través de sus paredes aisladas cuando la puerta se cierra durante dos horas. El 45% del calor y el 70% de la humedad ingresaron al cuerpo del camión en los primeros dos minutos de apertura de la puerta. Después del transporte y el almacenamiento previo a la venta con una duración total de 78 horas, se observó un fuerte crecimiento microbiano. El número de bacterias aumentó 5-6 veces en perejil y 3-4 veces en eneldo; Además, el perejil y el eneldo mostraron un aumento de 10 veces en hongos y levaduras en su superficie, respectivamente. Durante un período de tiempo similar, los mismos indicadores de hierbas frescas no sometidas al transporte y almacenadas en un refrigerador a condiciones estables de temperatura y humedad aumentaron solo 2 veces. Se ha demostrado que las fluctuaciones de temperatura y humedad en el cuerpo del camión también conducen a un cambio en la composición química de los vegetales durante el almacenamiento en frío adicional antes de la venta. Los datos obtenidos sobre la ganancia de calor durante el tiempo de apertura de la puerta deben tenerse en cuenta al calcular la capacidad de la unidad de refrigeración del camión.
Palabras clave: transferencia de calor y masa, condiciones de temperatura, hierbas verdes, distribución urbana, camión refrigerado, indicadores microbiológicos.

Introduction

The world food production is forecast to increase by 70% in the middle of the 21st century, which explains an increased importance of refrigeration technologies in preserving agricultural raw materials and food in order to provide consumers with high-quality products (Baranenko, 2017).

When assessing food safety hazards, it is necessary to take into account various sources of danger, the main of which is the temperature abuse during food transportation from manufacturer to consumer (Bogh-Sorensen, 2006; Munoz-Delgado, 1979).

Foods of plant origin are an extremely important source of nutrients. Depending on species and varietal characteristics, plant food losses can reach 30% during storage and transportation (Pusey, et al, 2009). For certain types of plant products, consumed mainly in fresh form, storage periods are limited and must not exceed several days. These include fresh greens, which are vegetative organs, most sensitive to microbiological spoilage (Blackburn, 2008; Kudryashova 1986).

Maintaining of required temperature allows reducing the intensity of plant breathing and biochemical processes and preserving the physical, chemical and sensory characteristics of products (SkorikovaYu, 1982). The reduction of losses and the preservation of quality through all the food supply system can be ensured by the cold chain maintaining a stable thermal state of foods (Encyclopedia «Food Technology»2019; Heap .2010).

Food transportation remains the weakest link between the manufacturer and the consumer, since it is at this stage that the cold chain control and temperature conditions often do not meet the safety requirements (Baranenko, 2010). Previous studies have shown that the most frequent and most significant temperature fluctuations occur during urban transportation (Gryzunov, 2019). This type of transportation differs from international, interregional and intercity transportation by a several unloading operations, since one truck usually delivers foodstuffs to several retailers. As a result, the external heat flow from the opened truck body significantly increases the temperature inside. An analysis of heat and mass transfer processes during the inter-city transportation will allow determining the actual heat load on a refrigeration unit and ensuring a rational operating mode for a refrigerator.

The monitoring of urban food transportations in Moscow (Gryzunov, 2014; Gryzunov, 2015) has shown that:

- only small and medium tonnage (from 0.8 to 4.0 tons) refrigerated trucks are used for this type of transportation;
- about 80.0% of the transported cargo are chilled food products, transported mainly at the temperature from 0 ° C to 4 ° C;
- the travel duration is from 5 to 8 hours;
- the number of product unloading points depends on the carrying capacity of the refrigerated truck used and the requirements of the consignee, and can range from 3 to 10;
- the average driving time between the points of unloading is from 35 to 40 minutes;
- the duration of unloading operations carried out with the vehicle open, is on average from 7 to 10 minutes.

According to a number of studies, in 1 hour of intra-city transportation in refrigerated trucks, the loss in weight can range from 0.35 ... 0.4% (pepper, zucchini, cucumbers, pears) to 0.6% (sweet cherry) and 1% (strawberries), and when transported at a distance of 25 ... 50 km - from 0.2 ... 0.9% (green vegetables) to 2.5% (dill, salad) (SkorikovaYu, 1982). At the same time, the nature of temperature and humidity fluctuations in the truck body and their influence on the quality indicators and microbiological contamination of foods, in particular, fresh fruit and vegetables are not well-studied.

Research goal

The goal of the study was to analyze the heat and mass transfer processes occurring in the refrigerator body at cyclic doors opening during urban transportation, and to determine their impact on microbiological indicators and chemical composition of transported leaf vegetables.

Methods

In line with the research goal, the two-stage experiment design was elaborated:

- at the first stage, heat and mass transfer processes occurring in the refrigerator body during urban transportation were studied;
- at the second stage, the effect of above processes on the microbiological and chemical parameters of green cultures was investigated.

A refrigerator truck «Gazelle» made in Russia with an isothermal body with a volume of 11 m^3 and a doorway of 3.4 m^2 equipped with a HT-100 ESCI refrigeration unit with a cooling capacity of Q_0 = 3089 W at t_0 = - 10 ° C and $t_к$ = 35 ° C was chosen as a research object.

The vegetative organs of green leafy vegetables, namely dill and parsley, were chosen as objects of study (transported cargo). This type of plant products is characterized by a weak water-holding capacity of colloids, slight water loss due to a highly developed leaf surface, thin ground tissue and cell walls, which allows to clearly monitor the influence of temperature fluctuations on the microbiota and the chemical composition of the product

The experiment consisted in measuring the temperature of outside air, air inside the truck body, the temperature of interior surfaces of the truck refrigerator and the surface of the transported cargo using Testo 735 instruments with operating temperatures from - 20 ° C to 50 ° C and measuring accuracy of ± 0, 05 ° C. The velocity of air outflow from the opened truck body doors was measured using Testo 425 anemometer with measurement range from 0 m / s to 20 m / s (measurement accuracy ± 0.03 m / s + 5% of the measured value). Relative humidity was measured using Testo 645 thermohygrometer (with relative humidity measurement range from 0% to 100%) with Testo humidity probe for measurements up to +125 ° C (error ± 2% RH at +25 ° C (+2. .. +98% RH) ± 0.1% RH / K (k = 1) long-term stability: ± 1% RH / year).

Sampling, preparing samples for analysis, seeding and determining the number of microorganisms was carried out using standard methods (Netrusov , 2005; GOST (All-Union State Standard) 31904-2012). The chemical composition and its changes during the experiments were determined with the use of existing methods (Maslovsky, 2017; Yermakov, 1987).

At first and second stages, the studies were carried out on the test bench where the following air parameters were maintained: temperature (22 ± 1) ° C, relative humidity (60 ± 2)%, natural circulation speed - up to 0.04 m/s.

First stage of experiment. The first stage of the experiment was carried out in empty truck refrigerator in accordance with the requirements of the ATP .

Temperature was measured using sensors installed according to the following scheme shown on Fig. 1:

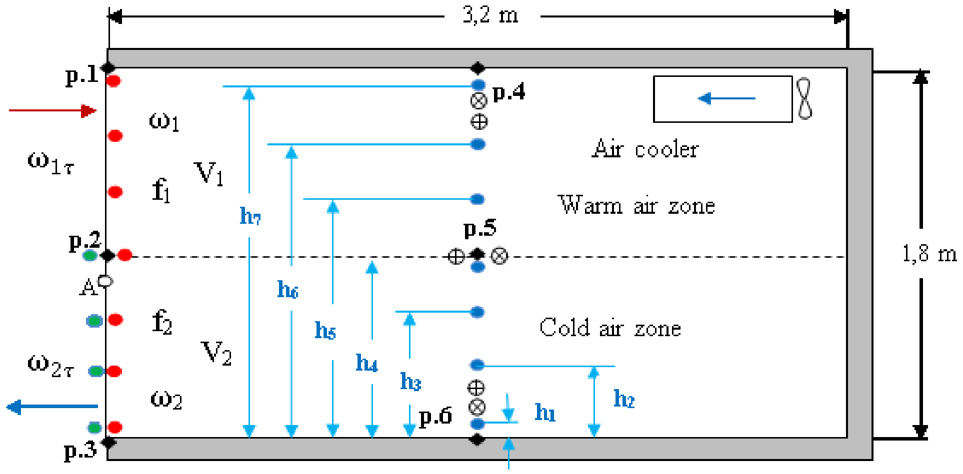

Figure 1. Diagram of measuring points for air parameters and side walls sur-faces temperature in a truck body with inner dimensions (3,2x1,9x1,8 m):

- ● – air temperature measuring pointsin the doorway;
- ● – air temperature measuring points in the truck body;
- ● – air speed measuring points in the doorway;
- ⊕ – air temperature measuring points on the side wall of the refrigerator;
- ⊗ – relative humidity measuring points inside the refrigeratoe;
- ◆ – truck body characteristic points (p.) - (p.1 – p.6);
- ○ – doorway zone (pointA),where the air speed is equal to zero;
- → – direction of inlet warm air flow;
- ← – direction of cold return air flow;

h_1 = 0,05 m; h_2 = 0,3 m; h_3 = 0,6 m; h_4 = 0,9 m; h_5 = 1,2 m; h_6 = 1,5 m; h_7 = 1,75 m

- air sensors in the doorway: in its geometric center (p.2, h_4 = 0,9 м); at a distance of 0.05 m from the center of the upper frame section (p.1, h_7 = 1.75 m); at a distance of 0.05 m from the center of the lower frame section (p.3, h_1 = 0.05 m); at a distance of h_2 = 0.3 m, h_3 = 0.6 m, h_5 = 1.2 m, h_6 = 1.5 m from p.3;
- air sensors in the truck refrigerator: in its geometric center (p.5, h_4 = 0.9 m); at a distance of 0.05 m from the geometric center of the ceiling (p.4, h_7 = 1.75 m); at a distance of 0.05 m from the geometric center of the floor (p.6, h_1 = 0.05 m); at a distance of h_2 = 0.3 m, h_3 = 0.6 m, h_5 = 1.2 m, h6 = 1.5 m from p.6;
- the sensors on inner surfaces of the body side walls at three points - in their geometric center and at a distance of ≈0.15 m from the floor and ceiling of the refrigerator.

The speed of inlet air was measured when the door was open in the center of the doorway at a height of $h_1 = 0.05$ m, $h_2 = 0.3$ m, $h_3 = 0.6$ m, $h_4 = 0.9$ m from the lower frame (p.3). Relative humidity was measured in the geometric center of the refrigerator (p.5), at the distance of 0.1 m from the floor (p.6) and at the distance of 0.1 m from the ceiling (p.4) of the truck body.

Temperature measurements were taken every 15 s, air speed and relative air humidity were measured every 60 s when the door was open.

The truck body was precooled during (60 – 90) minutes in the (0– 2) ° C mode, then the coolerswere turned off, and the doors were opened for (10 - 15) minutes, simulating the loading stage, and the cooling mode was switched back on. After 40 minutes of operation (a period of time equal to the average travel of the refrigerator from one unloading point to another), the refrigeration system was turned off, the doors were opened for 10 minutes (a period of time equal to the duration of unloading), then the door was closed and the refrigerating was turned on for the next 40 minutes. During the experiment, switching and door-opening cycles with a total duration of 50 minutes were carried out 6 to 7 times.

Second stage of experiment. Before this stage was started, freshly picked greens were placed for 24 hours in a cooling chamber with a temperature of (1–3) ° C, in accordance to the requirements of regulatory documents.
Then, a part of leafy vegetables from the cooling chamber was placed into the truck body, and the remaining part remained in the chamber at a temperature of (1 - 3) ° C as a reference sample not subjected to the urban transportation.

A sensor measuring air temperature in the truck body was placed in its geometric center according to the methodology described above. Sensors for measuring the product surface temperature were installed so that they had a maximum contact area with greens. Measurements of air temperature and product surface were taken at intervals of 60 s.

Before loading the green herbs into the truck body, a refrigeration unit was turned on for (60 - 90) minutes in the (0 - 2) ° C mode. At the end of loading, the door was closed and the refrigeration unit was turned on for 40 minutes. Then it was turned off and the door was opened for 10 minutes. Then the door was closed and the refrigerating was turned on again for 40 minutes. These cycles were repeated 6 –7 times within approximately 6 hours. Then, the herbs were unloaded and placed in small commercial refrigeratorwith a temperature regime of (1–3) ° C for 72 hours.

To study the microbiological indicators and chemical composition, samples of green herbs were taken before their storage in the refrigerator; after keeping them in the truck body; after their storage in small commercial refrigerator; after their storage in the refrigerator for 78 hours (control samples).

Results and Discussion

First phase of research.The pattern of temperature changes in the truck body during the door-opening tests is shown in Fig. 2.

The air temperature in the closed truck body ranged from -0.4 ° C to +1.4 ° C, while the air temperature in the upper part was approximately 1.0 ± 0.2 ° C lower than in the lower part due to the fact that the sensor was installed in the air flow from the cooler. On the contrary, when the door was open, the temperature in the upper part of the truck body was significantly higher than in the lower part, due to the intensive intake of warm air from outside.

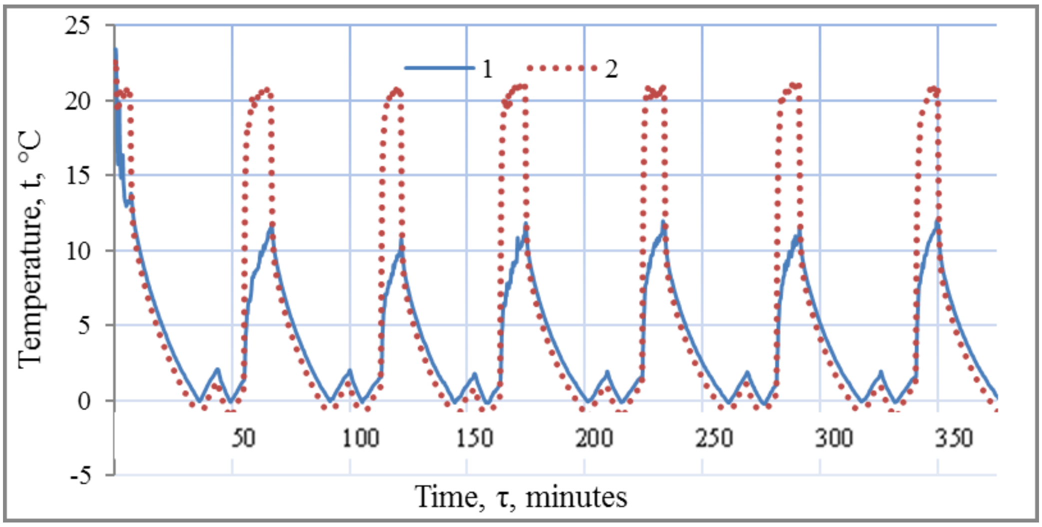

Figure 2. Effect of door-opening test duration on air temperature in the truck body.
1 – air temperature in the lower part of the truck body; 2 – air temperature in the upper part of the truck body.

The pattern of temperature changes at door opening is presented in Fig.3.

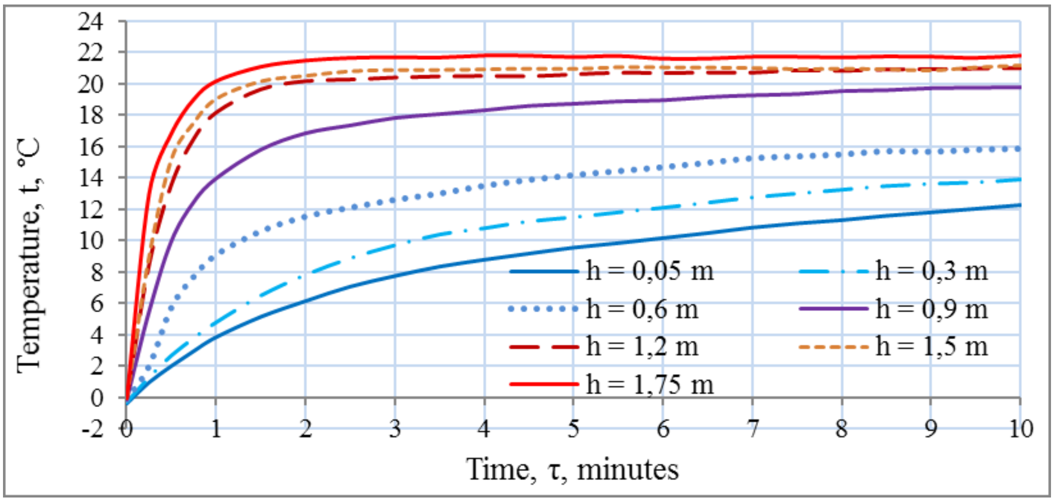

Figure 3. Kinetics of changes in the air temperature measured in the doorway plane.
h – distance between measuring point and the lower edge of door opening (p.3 on Fig. 1)

The air temperature measured at the moment of opening the door ranged from -0.4 ° C to 0 ° C. In the first two minutes, the temperature in the upper part of the opening sharply increased and reached the ambient temperature, which indicates the intensive infiltration of outside air into the truck body. The nature of air temperature change from the bottom of the doorway to its upper edgeindicates an active mixing of warm and cold air masses in its upper and central parts. The leakage of heavier cold air from the lower part of the body led to its gradual replacement with a mixture of external and internal air and, accordingly, to an increase in temperature at the bottom of the opening. Before closing the door, the air temperature in the upper part of the opening was (21.0 - 21.8) ° C, in the lower part - (12.3 - 16.0) ° C (see Fig. 3).

Figure 4 shows the average dependencies of the airstream velocity at the lower part of the doorway on the duration of door opening, obtained after pro-cessing the data of a series of experiments.

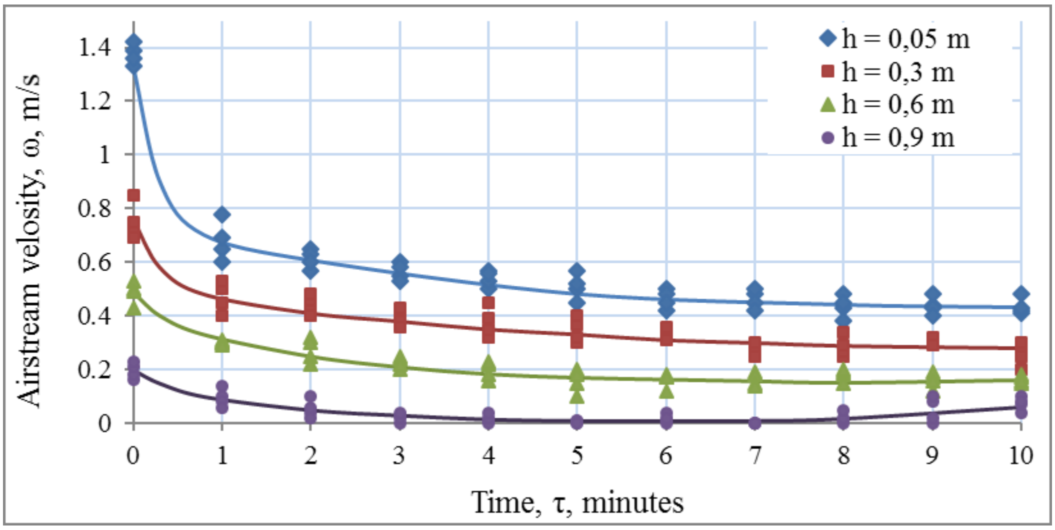

Figure4. Dependencies of airstream velocity on the duration of door opening, measured along the lower part of doorway plane
h – distance between measuring point and the lower edge of door open-ing (p.3 on Fig. 1)

The external air flow velocitiesat the top of the doorway showedwide variation, which indicates the instability of the air flow and relatively high turbulence when mixing air masses with different temperatures. The anemometer readings were relatively stable at heights h_1 = 0.05 m; h_2 = 0.3 m; h_3 = 0.6 m; h_4 = 0.9 m from p. 3 on the lower edge of the opening (Fig. 1). In the central part of the opening (p.2, h_4 = 0.9 m), the air stream velocity was minimal and ranged from 0.2 m / s to 0.06 m / s during the first two minutes, and over thetime period of (3 - 7) min was practically equal to zero, which indicates the balancebetween incoming and outgoing flows (Fig. 4). The increase in speed in p.2 - 7 min after the opening can be explained by the fact that the incoming air flow begins to dominate. The highest values of the outgoing air velocity were recorded at a height of h_1 = 0.05 m.

The pattern of air temperature changes in the central cross section of the truck body with the door open is shown in Fig. 5.

In the first minute, the air temperature in the upper part of the truck body (h_7 = 1.75 m) increasedsharply to 18 ° C, then the increase rate significantly declined and the relative temperature was found to be stableat (19.0 - 20.5) ° C after the second minute (Fig. 5). The air temperature in the lower part of the truck body (h_1 = 0.05 m) did not change much in the first minute, then it began to grow at a rate of (2.3 - 2.6) ° C / min until the 4th minute and continued further at a pace of 1.3 ° C / min to 0.6 ° C / min.

The relation between the inner side wall temperature on the height of the sensor and the door opening time are shown in Fig. 6.

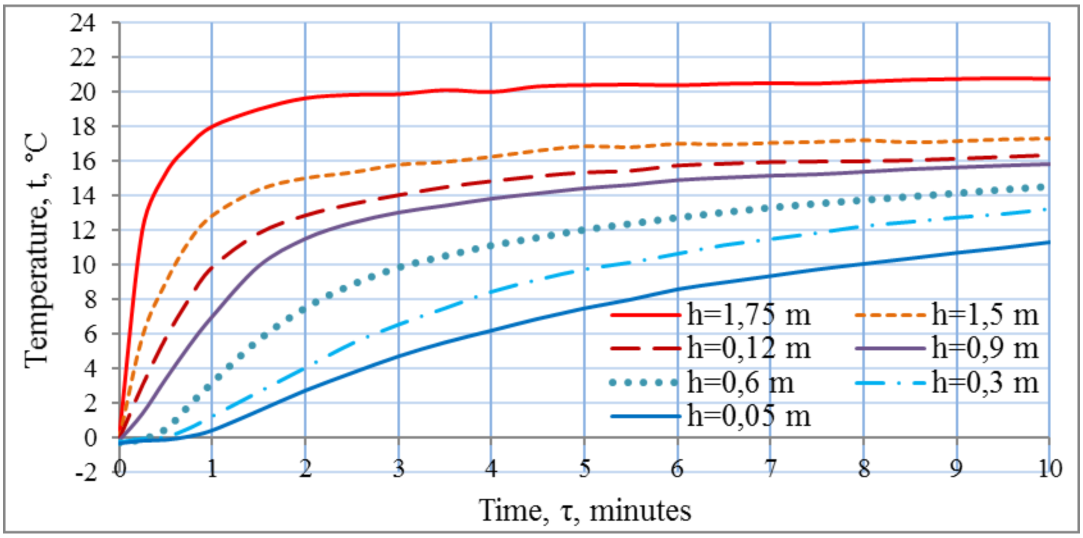

Figure 5. Kinetics of air temperature changes depending on the height measured along the cross-section of the truck body (p.4 - p.6) in the diagram (Fig. 1) with the door open
h - the height of the measuring point from the floor (p.6)

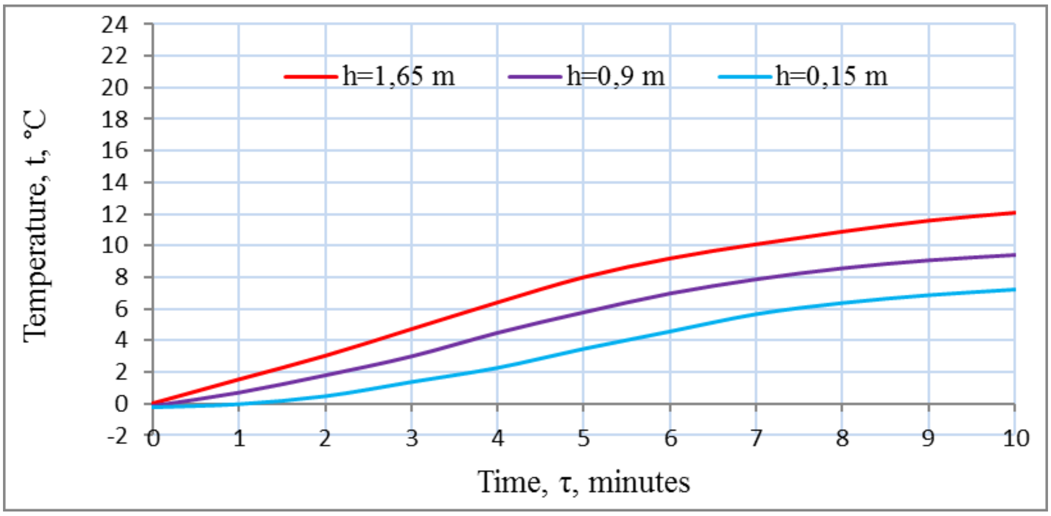

Figure 6. Kinetics of temperature change along the inner walls of the truck body with the door open
h - the height of the measuring point from the floor (p.6 on Fig. 1)

The inner wall temperature in the lower part of the body remained practically unchanged in the interval of (0 - 2) min, then it increased by (0.9 - 1.1) ° C per minute (Fig. 6). This can be explained both by the cold accumulation by metal structures, and by the presence of a stagnant zone in the middle and rear parts of the truck body at the beginning of the experiment. In the period of (0 - 10) min The wall temperature increased from (minus 0.1 - 0.4) ° C to (7.0 - 12.0) ° C depending on the sensor location.

Heat and mass transfer processes in the refrigerated body proceed according to the laws of free convection. The driving force is the temperature difference and, as a consequence, the difference in density betweenambient and internal air. At the initial moment of the experiment, this difference is significant, which results in a vortex circuit occurring in a limited space of the truck body. An active circulation of s of cold and warm air flows is observed and their active mixing in the first two minutes. At the same time, not only the temperature, but all the parameters of the air inside the truck body are constantly changing. By the end of the door opening time period, the intensity of the heat-mass transfer processes fades.

In order to simplify engineering calculations, let us accept that air thermophysical characteristics of (specific heat and density) are constant. The unsteady heat transfer process is divided into equal time intervals and considered tobe steady. In the framework of the identified steady processes, the parameters necessary for the calculation are in average values.

To calculate the heat gain at the moment of door opening using the principle of air flow continuity, let us assume that masses and flow rates of warm air intake and cold air leakage are equal to:

$$v_1 = v_2 \text{ , m}^3\text{/s} \quad (1)$$

where, v_1 is warm air volume flow rate, m^3/s;

v_2 is cold air volume flow rate, m^3/s.

The equation (1) may be expressed in the form:

$$f_1 \cdot \omega_1 = f_2 \cdot \omega_2 \text{ , m}^3\text{/s} \quad (2)$$

where, f_1 , f_2 are cross-sectional areas of warm and cold air flows respectively, m^2;

ω_1 , ω_2 are mean velocities of warm (across the area f_1) and cold (across the area f_2) air flows, m/s.

Let us find the mean velocity of warm air flow $\omega_{1\tau}$ for the estimated time interval τ_i , using equation (2):

$$\omega_{1\tau} = \omega_{2\tau} \cdot \frac{f_{2\tau}}{f_{1\tau}} \quad , \quad \text{m/s} \quad (3)$$

The assumption made allowed finding the mean velocity of cold air flowing outside $\omega_{2\tau}$ within time interval τ_i , using the following equation:

$$\omega_2 = (\omega'_{2\tau} + \omega''_{2\tau})/2 \quad , \quad \text{m/s} \quad (4)$$

where $\omega'_{2\tau}$, $\omega''_{2\tau}$ are mean velocities of cold air flow at the initial and final moments of time interval τ_i , respectively, calculated based on the data presented on Fig.4 for the area $f_{2\tau}$, m/s.

To calculate $f_{2\tau} / f_{1\tau}$, the location of point A on the doorway plane, where $\omega_{1\tau} = \omega_{2\tau} = 0$ was defined experimentally (Fig.1) for time interval τ_i . The height of p.A changed from 1.1m at the initial moment to 0.6 m before door closing.

The volume of warm air entering the body for a period of time τ_i is defined taking into account equations (2) and (3), as the following expression:

$$V_{1\tau} = \omega_{2\tau} \cdot f_{2\tau} \cdot \tau_i \text{ , m}^3 \quad (5)$$

where $V_{1\tau}$ is the volume of warm air, entering the truck body in time interval τ_i , m^3;

τ_i – calculated time interval equal to 60 s.

The heat gain Q_τ through the opened door for time interval τ_i can be calculated based on the heat balance equation:

$$Q_\tau = c \cdot \rho \cdot V_{1\tau} \cdot (t_{H_\tau} - t_{K_\tau}), \text{ kJ} \quad (6)$$

where c – mean specific air heat, kJ/(kg·K);

ρ – mean air density, kg/m^3;

t_{H_τ} – ambient air temperature, °C;

$t_{K_\tau} = (t'_{K_\tau} + t''_{K_\tau})/2$ is the average temperature of the air leaking through the doorway in time interval τ_i , °C;

t'_{K_τ}, t''_{K_τ} is the average temperature of the air leaking through the doorway at the initial and final moments of time interval τ_i , respectively, (Fig. 3), °C.

The results of calculation of Q_τ according to equation (6) are shown in Fig. 7. The calculations did not take into account the amount of heat released during moisture condensation, due to its insignificant amount.

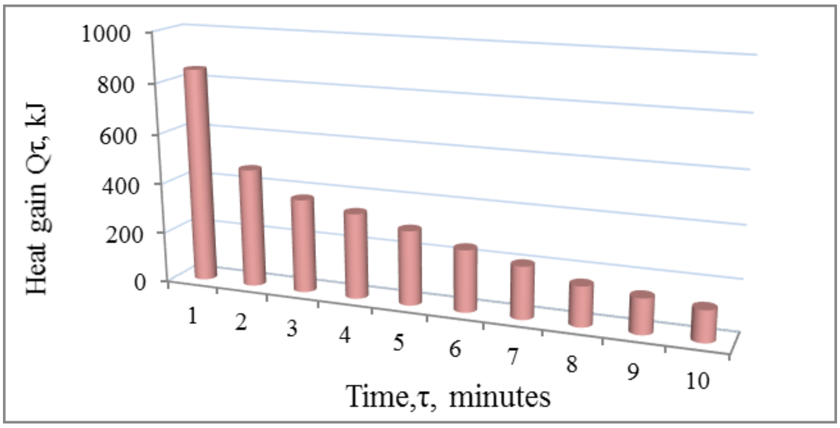

Figure 7. Dependence of heat load on the door opening time

The maximum heat gain was recorded in the first minute after door opening, in the second minute it decreased 2 times approximately, and then it decreased every minute by (10 - 15) %.

The relative humidity of the air in the closed truck body decreased during the experiments by about 20% compared to the ambient as a result of its drying when the refrigerating unit was on. After turning off the unit and door opening, the inner relative humidity increased during the first five minutes and reached the values shown in the graphs (Fig. 8). A more intense increase was observed in the upper part of the body, and then the humidity values in various parts gradually approached the ambient ones.

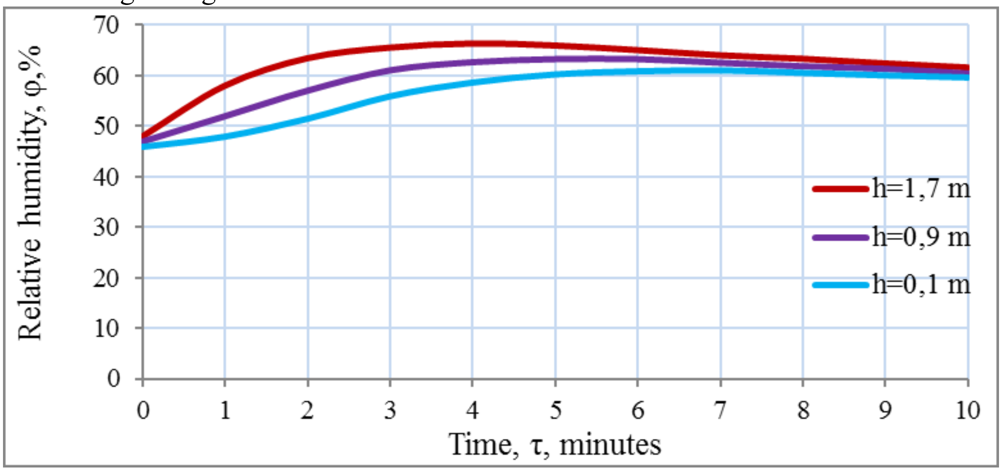

Figure 8. Influence of door opening time on the relative air humidity at differ-ent points in the truck body
h – the height of the measuring point from the floor (p.6 on Fig. 1)

The amount of water $W_τ$ condensed on refrigerated inner walls in time interval $τ_i$ is calculated as follows:

$$W_τ = M_τ \cdot (d_{н_τ} - d_{к_τ}) \cdot τ_i, \quad g \qquad (7)$$

where $M_τ = V_{f_{вл_τ}} \cdot ρ$ – is air mass flow rate across the area $f_{вл_τ}$, kg/s;

$V_{f_{вл}} = f_{вл_τ} \cdot ω_{1τ}$ – is air volume flow rate across the area $f_{вл_τ}$, m³/s;

$f_{вл_τ} = b \cdot b_{вл} + 2 \cdot h_τ \cdot b_{вл}$ – is the area of moisture condensation, m²;

$b_{вл}$ is the width of the area of moisture condensation. We assume $b_{вл} = 0.05$ (distance between the wall and temperature sensor location), m;

$b = 1{,}9$ is the inner width of truck body, m;

$h_τ$ is the height of side wall part where the moisture condenses within time interval $τ_i$, m;

$d_{н_τ}$, $d_{к_τ}$ are respectively the initial and final air humidity within time interval $τ_i$, g/(kg of dry air);

$τ_i$ – scalculated time interval equal to 60 s.

$h_τ$ is calculated to ensure moisture condensation based on experimental data (Fig. 5, 6 and 8) for calculated time interval .

The results of $W_τ$ calculation from equation (7) are presented on Fig. 9.

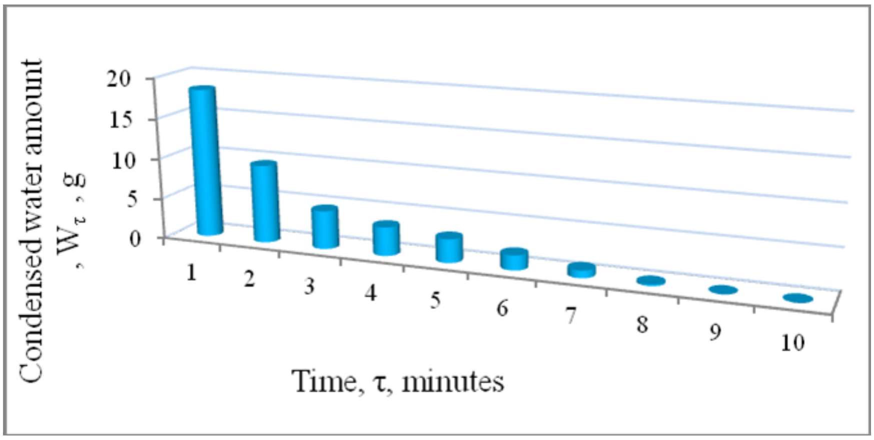

Figure 9. Influence of door opening time on the amount of water, condensed on the inner truck body surfaces.

The process of water condensation on the ceiling began 30 seconds after door opening, and active condensation on the surface of ceiling and adjacent surfaces of the walls began 60 seconds after the door was opened. After (2 - 3) minutes, condensate appeared on almost the entire surface of the side walls, except their lower parts and the floor. The amount of precipitated water was maximum in the first minute, and minimal in the interval of (7-8) minutes.

The study results showed that heat and mass transfer processes in the refrigerated truck body are unsteady when the door of truck body is open, assuming that the door is one of its walls. Continuous air exchange with the environment, active circulation through the doorway and mixing of warm and cold flows lead to a constant change in air parameters (speed, temperature, relative humidity) inside the truck body. With opened door, heat gain in 10 minutes is comparable to the heat influx through the body envelope in 2 hours with door closed.

During the door opening time, the internal air temperature almost reaches the ambient, which leads to increased temperature of internal truck body surfaces. With the door closed, the rate of cooling is lower than the rate of heating when the door is opened, so the air temperature in the truck body significantly exceeds the preset temperature regime for a considerable time.

When the door is opened, water condenses on the inner surface of the body, and its amount increases along with relative humidity inside and increased difference between outside and inside temperature. During the refrigerating unit operation, the condensate evaporates almost completely from the metal lining of the body onto the air cooler. However, in the case of transportation of products with high water-holding ability, part of the condensate may remain on their surface.

The air temperature exceeding the required one for a considerable time (more than 60% of the total inter-city transportation (Fig. 2)), and the presence of condensate create favorable conditions for the development of microorganisms. To confirm this conclusion, the second stage of research was performed.

Second phase of research. At the beginning of the experiment, the following operations were consistently implemented: truck body pre-cooling, removing part of green herbs from the refrigerator, placing sensors, loading the products into the body. The process of loading green herbs took about 15 minutes, during which the inner air temperature increased to (18.5 - 19.0) ° C, and the greens surface temperature - to (7.7 – 8.3) ° C.

The pattern ofair temperature change in the truck body isin a good agreement with the data obtained at the first stage of research (Fig. 10).

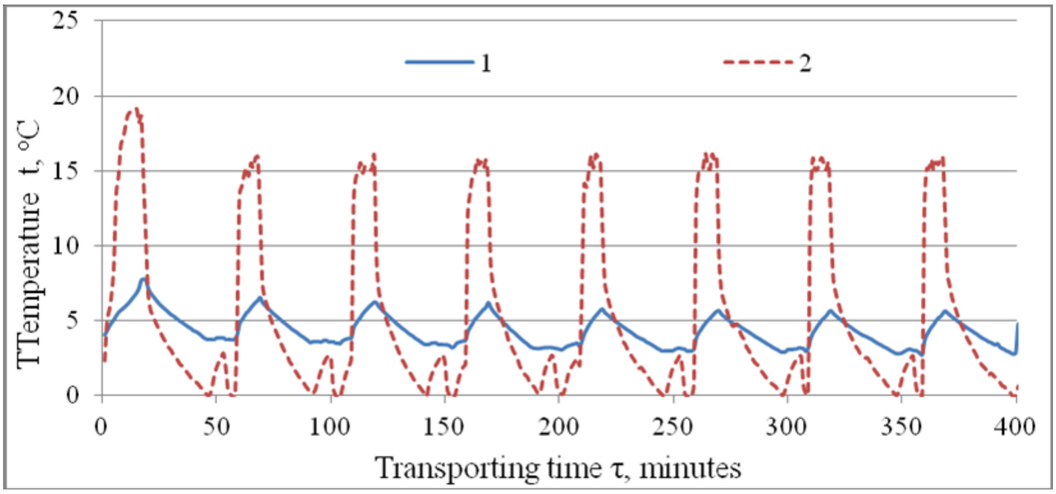

Figure 10. Influence of transporting time on the inner temperature of refrigerated truck body and greens surface temperature during the inter-city multi-drop delivery.
1 – product surface temperature; 2 – air temperature in the truck body

During 10 minutes door opening, the surface temperature of transported product increased by (3.0 - 3.5) ° C., and a finely divided water condensate was formed on the inner wall surfaces and on the surfaces of transported product.
When the door was closed, the required air temperature (0 - 2) ° C inside the truck body was obtained in only (28 - 30) minutes. By the moment of the next door opening, the surface temperature of transported greens decreased to (3.3 - 4.0) ° C.
The results of microbiological studies are presented in Figure 11.

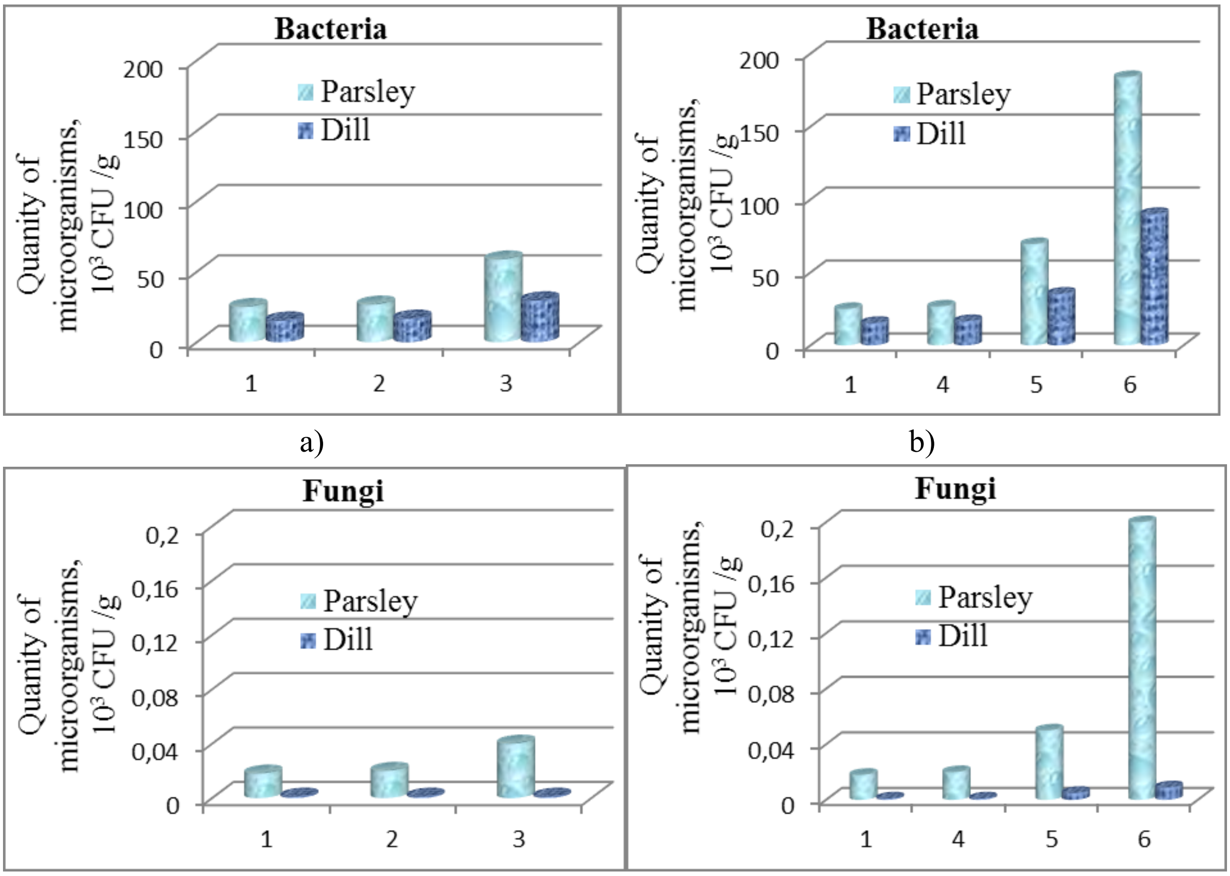

Figure11. Changes in the quantity of microorganisms on the surface of greens (parsley and dill) during short-term storage, transportation and sale

1 – before putting into refrigerated room (control); 2 – after 24 h storage at (1 – 3) °C; 3 – after 78 h storage at (1 – 3) °C; 4 – after 24 h cold storage at (1 – 3) °C and before transportation; 5 –after transportation at (0 – 2) °C during 6 hours; 6 –after 72 h storage in commercial refrigerator at (1 – 3) °C.

The greenskeptfor 78 h in a cold room showed an approximately double increase in the quantity of microorganisms compared to the control values before putting them into storage (Fig. 11 a, c, e).
After transportation, the number of bacteria significantly increased by 2.8 times on parsley, and by 2.3 times on dill, and on parsley, so that on parsleythere were about 2 times more bacteria than on dill (Fig. 11 b). Changes in the quantity of fungi (on dill) and yeasts (on parsley) after transportation were extremely insignificant (Fig. 11 d, f). At the same time, yeasts and fungitotal number increased by 2.7 - 2.8 times.
Further 72 hours storage in commercial refrigerator resulted in a sharp growth of microorganisms. The number of bacteria increased by 5–6 times compared to control values in parsley, and 3–4 times in dill (Fig. 11 b), the same was true for fungi on parsley (Fig. 11 d) and yeast on dill (Fig. 11 f): their quantity increased by 10 times.
The results point to a beneficial effect produced by thermal discontinuities and water condensation on the reproduction of microorganisms.
During transportation and storage of plant products, including leafy green vegetables, important changes occur in their consumer properties. This is the result of physical (temperature changes), biochemical (respiration) and chemical (hydrolytic decomposition of complex organic compounds to simpler ones) processes in plant products.
Temperature fluctuations during the transportation period had contributed to a decrease in the content of beneficial substances in plant products after short-term storage of leafy greens before sale, which reduced their nutritional and vitamin value (tables 1 and 2).

Table 1– Changes in chemical composition of greens (dill)

Chemical composition	Content			
	water, %	sugars, %	Ascorbic acid, mg %	Etheric oils, mg %
Control				
Before putting into storage in a refrigerated room	86,3	6,8	102,5	1,5
During cold storage (experiment)				
After 24 h cold storage at (1 – 3) °C	85,1	6,5	98,4	1,4
After 78 h cold storage at (1 – 3) °C	81,2	6,1	80,3	1,0
During transportation and storing before sale (experiment)				
Before transportation and after 24 h cold storage in a refrigerated room at (1 – 3) °C	85,1	6,5	98,4	1,4
6 h storage after transportation at (0 – 2) °C	83,7	6,3	90,5	1,4
After 72 h storage in a commercial refrigerator at (1 – 3) °C	76,5	4,9	53,8	0,7

Table2– Changes in chemical composition of greens (parsley)

Chemical composition	Content			
	water, %	sugars, %	Ascorbic acid, mg %	Vitamin A, mg %
control				
Before putting into storage in a refrigerated room	85,3	6,9	152,3	953,0
During transportation and storing before sale (experiment)				
After 24 h cold storage at (1 – 3) °C	84,6	6,6	145,8	950,0
After 78 h cold storage at (1 – 3) °C	80,7	5,6	109,7	895,7
During transportation and storing before sale (experiment)				
Before transportation and after 24 h cold storage in a refrigerated room at (1 – 3) °C	84,6	6,6	145,8	950,0
6 h storage after transportation at (0 – 2)	83,4	6,2	130,9	924,0

°C				
After 72 h storage in a commercial refrigerator at (1 – 3) °C	76,8	4,3	96,2	728,0

Thus, temperature breaks during transportation and dropwise condensation on the external tissues of green herbs create favorable conditions for the development of microorganisms and lead to a change in the chemical composition of the product.

Even if, after transportation, plant products are stored in a refrigerator at a stable low temperature, the process of pathogenic development does not stop, but, on the contrary, the number of microorganisms increase, which can ultimately result in a microbiological spoilage of products and a decrease in their nutritional value.

Conclusions

During the urban multi-drop transportation of plant products, the amount of heat entering the truck body during short-term door openings (when unloading parts of transported cargo) is comparable to the heat influx through its enclosing structures with the door closed for two hours.

Up to 45% of total heat gain and 70% of moisture enters the truck body within the first two minutes after the door opening. Therefore, the change in the heat-moisture balance in the truck body is more dependent on door opening frequency than on duration. This fact must be taken into account when calculating the cooling capacity and choosing the refrigeration unit for the truck.

The warm outside air entering the truck body causes water condensation on the inner walls of the body and the outer surface of the cargo being transported. Fresh green products must be protected from condensation during urban transportation.

Fluctuations in temperature and humidity in the refrigerated body lead to an accelerated development of microorganisms and change in the chemical composition of product during further cold storage before sale.

The obtained results broaden the existing idea of heat and mass transfer processes occurring in the refrigerator during urban transportation and affecting the safety and quality of products; they also confirm the importance of stabilizing the temperature and humidity of the environment during transportation and storage.

References

1. Baranenko A.V. (2017) Fundamental aspects of world civilization / A.V. Baranenko // Russian magazine «Empire of Cold»–№ 3. – P. 38–39.
2. Bogh-Sorensen, L. (2006). *Recommendations for the processing and handling of frozen foods*. International Institute of Refrigeration.
3. Munoz-Delgado, J. A. (1979). Recommendations for chilled storage of perishable produce. Annexe au Bulletin del'institut international du froid, 148.
4. Pusey, P. L., Stockwell, V. O., & Mazzola, M. (2009). Epiphytic bacteria and yeasts on apple blossoms and their potential as antagonists of Erwinia amylovora. Phytopathology, 99(5), 571-581..
5. Blackburn, C.deW., (2008). Microbiological spoilage of food products. St. Petersburg: Profession. -784 p. ISBN 978-5-93913-146-9 (in Russian)
6. Kudryashova A.A. (1986) Microbiological basis for fruits and vegetables preservation / A.A. Kudryasheva. - M .: Agropromizdat.. – 189 p.
7. SkorikovaYu.G. (1982) Storage of vegetables and fruits before processing / Yu.G. Skorikova. - M .: Light industry.–. – 200 p.
8. Encyclopedia «Food Technology». (2019) Volume 16 «Technologies of refrigerated processing and storage of food products», book 2. - LLC «Publishing House Uglich»,. – 298 p.
9. International Institute of Refrigeration, & Heap, R. D. (2010). *Guide to refrigerated transport*. International Institute of Refrigeration.
10. Baranenko A.V., (2010) Continuous cold chain as the basis for resource saving and food safety strategy / A.V. Baranenko, G.A. Belozerov // Russian magazine «Refrigeration». – № 3. – P. 9–12.
11. Gryzunov A.A., (2019) Classification of specialized vehicles for urban transportation of chilled food

products / A.A. Gryzunov, V.N. Kornienko, S.V. Avilova, A.G. Donetsk // Russian magazine «Refrigeration». № 6. - P. 34–38.

12. Gryzunov A.A., (2014) Structural analysis of refrigerated vans for inner city transportation of perishable foodstuffs / A.A. Gryzunov, V.N. Kornienko // Russian magazine «Refrigeration equipment». No. 12, - P. 45 - 48.

13. Gryzunov A.A. (2015) Verification of the conformity of food transporting vehicles thermal characteristics with international standards / A.A. Gryzunov, V.N. Kornienko // Russian magazine «Refrigeration equipment». - 2015. - № 5. - P. 47-50.

14. Netrusov A.I. (2005) Practical Course on Microbiology / A.I. Netrusov, M.A. Egorova, L.M. Zakharchuk. - M.: Academy,– 608p.

15. Krasnikova L.V. General and Nutritional Microbiology: A Training Manual. Part I. / L.V. Krasnikova, P.I. Gunkova. - SPb .: ITMO University. – 2016. – 134 p.

16. GOST (All-Union State Standard) 31904-2012. Food products. Sampling methods for microbiological research.

17. Maslovsky S.V. (2017) Laboratory and practical training on «Technology for storing fruits, vegetables andproducts of their processing» / S.V. Maslovsky, N.A. Piskunova, Sh.V. Gasparyan, S.V. Avilova, V.A. Borisov, A.V. Romanova. - M.: Publishing house of the RSAU - MAA. –162 p.

18. Metlitsky L.V. Biochemistry of fruits and vegetables. / L.V. Metlitsky. - M.: Economics. - 1970. – 271p.

19 Yermakov A.I. (1987) Methods of biochemical study of plants / Yermakov A.I., Arasimovich V.V., Yarosh N.P. et al.; edited byYermakov A.I. 3rd edition,revised and updated. Leningrad.: Agropromizdat. Leningrad branch. –430p.