DESIGN AND FULL-SCALE TESTS OF A MICROCLIMATIC CONTAINER FOR TRANSPORT OF FROST-SENSITIVE FREIGHT UNDER ARCTIC CONDITIONS

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We consider the procedure and the results of solution of the problem of safe transportation and long storage of fruit and vegetable products under Arctic conditions in containers inside which an optimal theoretically based thermal humid air regime is kept.

Nowadays supplying the population of the regions of the Far North with fruit and vegetable products is an urgent problem, whose solution is contigent on finding and using effective means and technologies of large-scale fruit and vegetable transportation. For the most part these freights are delivered to the Far North regions during the after-harvesting period, i.e., during autumn and winter months when the air temperature gives no way of transporting these freights by standard means, i.e., in transport ship holds. One of the procedures of solving this problem is to use isothermal containers keeping a microthermal humid air regime in the freight when transporting from door to door of vegetable storehouses.

Designing such containers is hampered by the lag of the theory of engineering provision of a microclimate in freight. Freight preservation during transportation and storage is affected by many factors, but first of all by temperature and moisture content regimes. The most important thermophysical process affecting the preservation of vegetable products is mass exchange of the products with the environment. As a result of this process substantial fading of a product or its sweating may be exhibited. Both these phenomena weaken the natural stability of living vegetable tissue toward microbiological diseases and result in considerable losses of products.

Unlike other kinds of products, fruits and vegetables are more sensitive even to inconsiderable changes of the microclimate parameters and go bad more quickly because of continuous release of physiological heat, carbon dioxide, moisture and other components influencing their preservation and ripening [1, 2].

The problem of conditioning vegetable products is to retard all undesirable processes and, in particular, biochemical ones. The rate of these processes depends on the microclimate in the finite freight volume.

The present article is aimed at revealing regular trends in the formation of temperature-moisture content fields in freight, at finding the means of impact on thermal-humid air processes inside a container, and at making engineering recommendations on designing, manufacturing, and heat engineering testing of microclimatic containers (MCCs).

Constructional Features of a Microclimatic Container. As a result of preliminary scientific-technical research, a twenty-foot 39 m^3 container 1SS manufactured at domestic factories is utilized as a base (initial) model of a container which can be adapted to an isothermal one.

The container was adapted using preliminary heat engineering and physical calculated data as the base with regard for the biological processes of breathing of vegetable products planned for transportation and temporary storage in a container.

Extensive optimizational computer experiments establish that the MCC insulation thickness must not be uniform: it is 0.08 m for the floor and side walls and 0.1 m for the ceiling when foam-polyurethane insulation is used

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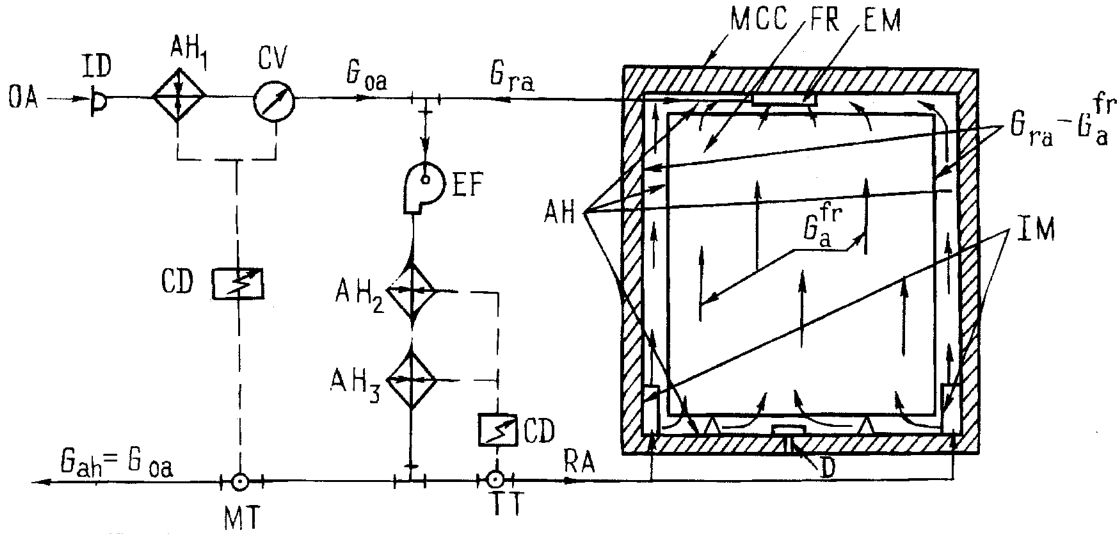

Fig. 1. Basic diagram of the microclimatic installation (MCI): OA, outdoor air; G_{ra}, recirculating-air flowrate; IM, intake main; EM, exhaust main; AH, air hole; ID, intake device; AH_1, outdoor air heater; CV, control valve; EF, electric fan; AH_2, AH_3, linear air heaters; TT, temperature transducer; MT, moisture-content transducer; CD, converting device; D, drainage.

($\lambda = 0.035$ W/(m·K)) [3]. The insulation is installed using aluminium sheets, whose joints are waterproof (see Fig. 1).

To provide removal of heat and moisture caused by the breathing of the products as well as air heating and circulation a microclimatic installation (MCI) is designed which is composed of two fans, four independently controlled tubular electric heaters (TEHs), measuring devices for controlled parameters, and automatic units for MCI operation. The MCI is located behind a fence in the top part of the container wall opposite to the doors and isolated from the containerized freight and the environment.

The electric shield and the instrumentation panel are mounted behind the MCI fence, and access to them and the remaining objects of the MCI is gained through two hatches made on the back container wall and closed with covers.

Such constructional features of the MCC with regard for the power of the mounted TEHs stated below keep a maximum temperature of +16 ± 1°C inside the container at a minimal environmental temperature of -20°C. A given air temperature inside the container is kept automatically irrespective of the outdoor air.

Forced air circulation through the freight to be transported is provided by a system of two fans and three air ducts. All three air ducts are located along the entire length of the container: intake ones, at the bottom, near the floor; an exhaust one, at the top, under the ceiling. Holes are drilled along the air ducts and are shut off with control valves to maintain constant air flowrates along the entire length of the container. The admission holes for the fresh outdoor air (admixture) to be added to the circulation system are on the outer wall of the MCI and the drain ones, on the side walls of the container near the doors. Primary heating of the added air to +4°C is provided for, irrespective of its flowrate. The amount of the added air is controlled stepwise, and its maximum volume attains 50 n.m^3/h. The power of the mounted fans allows recirculation of the entire MCC air in a volume of at least 1500 n.m^3/h. Such are the constructional and general characteristics of the isothermal MCC designed within the context of the present study.

Freight Transport Regimes. In designing and calculating the MCC the problem was stated of providing safe (not limited in time) transport of twelve kinds of root crops, vegetables, and fruits at a minimal environmental temperature of -20°C. The corresponding calculations of transport regimes are made for all twelve kinds of products, having regard for their biological distinctive features. Calculations of the regimes of safe transport of vegetables and fruits first of all allowed for breathing heat liberation, oxygen absorption, carbon dioxide release, moisture release, and the possibility of the container walls and ceiling to sweat due to these processes. To provide conditions of safe transport of such products problems of their preliminary cooling and ripening in transportation, possible pathological

TABLE 1. Thermophysical and Biochemical Characteristics of Potatoes and Lemons

Parameter	Potatoes	Lemons
Storage temperature	3	6
Density		
physical	1080	730
bulk	650	440
Porosity factor	0.4	0.4
Mean diameter of raw material	0.04	0.06
Specific surface of heat transfer	0.185	0.182
Evaporative capacity of raw material	0.012	0.07
Specific surface of mass transfer	0.00222	0.01274
Breathing heat at ^{o}C	0.01	0.01111
Temperature coefficient of breathing	0.062	0.0718
Heat release of 1 kg of raw material at the transport temperature	0.012	0.01711
Specific heat capacity of raw material	3.62	3.77
Equivalent diameter of pores	0.01333	0.0199
Form factor	0.325	0.22

TABLE 2. Optimal Transport Regimes of Fruit and Vegetable Freights in an MCC

Transport parameters	Freight type	
	potatoes	lemons
Air temperature	3—4	6—12.5
Relative humidity	85—90	80—90
Mean air velocity in an MCC	0.15	0.20
Ventilation ratio	2	3

changes when affected by biochemical processses, and, as a result, forecasting natural loss of the products to be transported were considered.

Along with this, in specific transportation it is necessary to take into account the mode of transport, the type of packing and, as a consequence, the organization of a rational air circulation system.

Also, it should be allowed for that transportation and storage of containerized vegetables and fruits have some specific features attributed to the small freight volume of the container and the large loading volume of the freight. This results in convective heat transfer enhancement between the walls and the freight, drag increase, and possible development of stagnation zones.

The range of optimal transport and storage temperatures of the twelve freights for which the MCC has been designed is from -2 to +12^{o}C. Thermophysical and biochemical characteristics of these products are systematized according to literature data. On the basis of literature recommendations and standards, optimal transport regimes of all vegetable products considered in the present article are specified. Tables 1 and 2 present as an example such data for potatoes and lemons as the most typical freights planned for MCC transport.

Air Distribution System. Requirements for the air distribution system are prepared with regard for the special features of transport of fruit and vegetable freights in an MCC . The major specific feature of the air distribution system is that the recirculating-air (RA) flow disintegrates at the freight volume entrance. The greater part of the flow is directed, bypassing the freight, into vertical clearances (air holes) formed between the inner fences of the MCC and the freight surface. This part of the flow compensates ("catches") heat losses through the container walls.

A smaller part of the flow is directed into a clearance formed between the container floor and the freight, and compensates heat losses through the floor. This air flow, passing through the freight upwards, removes the products of vital activity (heat, moisture, carbon dioxide, etc.). In the top part of the container both flows merge into one flow streamlining the ceiling and being cooled to a minimal temperature in the freight compartment. The air enters the electric-type air heater through the container exhaust duct. In a suction receiver of the fans the outdoor air is added to the recirculating air. Its amount is controlled by the drag of the supply main (by the number and the degree of opening of the outdoor air suction holes). A mixture of the recirculating and outdoor air flows heated by their independently controlled TEHs is pumped by centrifugal fans into the air distribution header of the MCC. Thus, a closed air circulating loop is formed.

Air flow disintegration into two parts is performed, assuming provision of breathing heat removal from the freight. So, for example, in potato transport at $t = \pm 3^{\circ}C$ $q_{br} = 12 \cdot 10^{-3}$ W/kg (see Table 1). At the nominal container charge $M^{fr} = 8000$ kg and maximal recirculating-air heating by $1^{\circ}C$ the air flowrate (G_a^{fr}) passing through the freight is 360 kg/h and is calculated from the heat balance:

$$M^{fr} q_{br} = c_{pa} G_a^{fr} \Delta t_a^{fr}. \tag{1}$$

Such an air distribution system provides complete compensation of heat losses through the MCC fences and removal of the products of the vital activity of the transported freight without substantially decreasing the useful volume of the container. Thus, the freight storage is practically kept in an "adiabatic" membrane, and moisture condensation on the inner surfaces of the MCC is excluded.

Heat-Moisture Content Characteristics of an MCC. Calculations and studies of the thermophysical parameters of interacting media and of the mass transfer characteristics of an MCC were made on computers. In doing so, temperatures of the inner fences, differential and total losses through the fences, moisture precipitation coefficients, parameters of the freight and moist air at specific points, as well as parameters of the MCI as a whole were determined.

These studies were aimed at finding an optimal value of t_1 of the air flow at a given freight transport temperature t^{fr}. Analysis of the obtained results permitted one to establish the following general distinctive features of heat and mass transfer processes in the designed MCC. With rise in the air temperature at the entrance to the freight t_1, its φ_1 and φ_2 decrease. However, the curve $\varphi_1 = f(t_1)$ is always steeper than the curve $\varphi_2 = f(t_2)$; therefore, they intersect at a certain value of t_1. This means that at a given temperature an isosteric (φ = const) heat and mass transfer process occurs in the stack of freight. It is found that the higher the evaporative capacity of the raw material the greater is the value of φ in the isosteric process (for citrus plants $\varphi = 1$).

In designing MCCs their heat-moisture content characteristics under freight cooling were analyzed, too. This is performed when the MCC is detached from the electric circuit, e.g., during freight handling.

The conditions for transport of the twelve freights were analyzed within the framework of the considered study. When analyzing and making recommendations on transport the initial prerequisites were those common to all modes of freight: transport temperature and relative moisture content must be constant and optimal because of their control during the whole period; drying loss magnitude D must not exceed the established standards, the freight must not lose turgor, but on the other hand, mold must not appear.

The heat-moisture content characteristics of the processes occurring in the MCC have been constructed for each kind of products. Such optimal parameters for two freights are given as an example in Table 3.

Graphical processing of the potato data establishes that for an optimal moisture content of the air inside the stacks of $\varphi = 87.5\%$ the air temperature at the entrance to the freight must amount to $2.67^{\circ}C$. The parameters of the recommended (optimal) MCI operation (see Table 3) are determined from this value of the temperature.

Generally, the heat-moisture content controlling system is very sensitive to the temperature t_1. However, the heat-moisture content characteristic of the MCC in potato transport is relatively stable and can provide safe transport at a fluctuation of t_1 from 2.5 to $3.0^{\circ}C$. In this case, a maximum value of D is 0.048% a day. At t_1 below $2.5^{\circ}C$ moisture condensation is seen on the inner surfaces of the container.

The regime of lemon transport substantially differs from the optimal ones of other vegetables and fruits. Thus, a relatively high temperature of their transport ($+6^{\circ}C$), as compared to oranges and tangerines ($+3^{\circ}C$),

TABLE 3. Heat-Moisture Content Characteristics of an MCC

Parameter	Transported freight	
	potatoes	lemons
Recommended:		
temperature of freight transport	3	6
humidity of air inside a stack	85—90	80—90
Amount of supplied outdoor air	29	59.5
Temperature of installing temp. controller	2.8	6.35
Value of installing a moisture controller	85	90
Air temperature at entrance to freight	2.7	6.4
Temperature drop of air flow in freight	0.3	—0.4
Drop in rel. air flow humidity in freight	3.1	14
Mean consumed power	0.55	0.59
Natural loss of freight	0.034	0.086
Moisture condensation on a surface	Traces	Traces
Cryoscopic temperature	—1.34	—2.07
Available transport time of a container with no heating at		
$t_{cut} = -20^oC$	32	32
$t_{cut} = -50^oC$	12	12

predetermines the distinctive features of their transport and storage. In particular, the moist regime of containerized transport of lemons is observed at an air temperature at the entrance to the freight from $t = 6.3^oC$ and below. This corresponds to the maximum allowable value $\varphi = 86\%$. Therefore, the regime consistent with $t_1 = 6.4^oC$ (see Table 3) should be taken as the optimal one.

Similar analysis of the remaining ten kinds of vegetable and fruit goods has shown that they can also be transported safely in the designed MCCs by complying with the optimal transport parameters (t^{fr} and φ^{fr}).

According to the intensity of outdoor air ventilation (according to the admixture amount) of the studied goods, the latter may be subdivided into two groups. 30 kg/h of outdoor air must be added for potato, onion, garlic, and apples and 60 kg/h for cabbage and cauliflower, beet, carrot, cucumber, and all citrus.

The available transport time with no heating (see Table 3) is ultimately allowable and is found from the condition of temperature field uniformity in the freight. Undoubtedly, the freight handling time should be reduced.

Relying on theoretical calculations, four MCCs were manufactured in two modifications. After two experimental specimens were manufactured and tested, some alterations are made in the MCC design. These are: additional insulation of the MCI walls to decrease heat transfer, increase of the power of the heating elements from 1.85 to 2.35 kW by installing three additional TEHs and by arranging closed air recirculation. Commercial tests of the last MCC specimens showed the possibility of keeping the container temperature by 36°C higher than the environmental one.

Full-Scale Tests of MCCs. Full-scale tests of MCCs were made on the Murmansk-Dudinka-Norilsk route for the winter-spring period of 1990. The first-modification MCCs (open air recirculating loop in the MCI) were tested from February 9 to 26 in potato transport on the SA-15 ship twindeck. The second-modification MCCs were tested from April 7 to 18 in fresh-lemon transport on the ship deck. In both cases, heat engineering tests were made according to the preliminarily developed programs.

The air temperature overboard in the first run varied from 0 to -25°C, and on the twindeck, from +3.5° to -8.2°C. In the second run the lowest temperature overboard was -17°C.

Preliminarily checked standard and portable measuring devices were used to measure temperature, moisture content, air velocity, and consumed power of the MCC. Temperatures were measured by copper-constantan thermocouples and thermometers; moisture content, by sorption hygrometers; electric power, by a wattmeter; air velocity, by an anemometer.

The temperature at different points of the container and freight was measured by eight thermocouples. A TS-80 unit installed in the MCI served as a stationary facility for measuring temperature. Its sensing elements were mounted in the air flow at the exit from the freight compartment of the MCC (in front of the main TEHs) and near the inlet pipe of the fans.

The air humidity was measured from the side of the MCI by a stationary GS-210 and from the side of the MCC doors by a portable sorption hydrometer, whose first converter was placed into the stack of the freight.

The air velocity in the suction and flow-off holes was measured by a revolving-vane anemometer. The data obtained were used to calculate circulating-air volumes and to determine air inflows and flow-off.

The containers were placed to be accessible for inspection from three sides. The thermocouple leads and the cold junction were brought out to the MCC doors and welded to the joint. The thermocouples were connected to the potentiometer via an eight-point switch combined with the thermocouples by means of the joint. The cold junction was placed in a Dewar flask, in which the temperature of thawing ice was constantly maintained.

A temperature value corresponding to the standards of safe transport and storage of goods was established from the indications of a temperature sensing element mounted on the MCI control panel.

The thermophysical parameters of the air and the freight were measured several times a day. The obtained results of MCC tests were processed and tabulated. Analysis of the obtained data permitted one to draw some important conclusions, which were taken into account in manufacturing a second modification of test specimens of an MCC and in conclusions and recommendations on full-scale production of MCCs.

Scavenging-air flowrates vs the degree of opening of the flow-off holes and the number of open inflow holes were studied from the measured air velocity data. In the second-modification MCC significantly good air exchange took place. Thus, when one inflow hole (∅ = 46 mm) is open, the scavenging-air flowrate amounts to 13.45 kg/h and when two are open, 15.7 kg/h.

Conclusions. Full-scale tests confirmed that the designed MCC was applicable for vegetable and fruit transport under Arctic conditions. In test transport of potatoes and lemons in an MCC , an optimal temperature-moisture content regime of transport was provided, which was certified by a commission. Optimal (preliminarily calculated) transport regimes were provided by opening a certain number of air inflow holes for each mode of the freight and by assigning a transport temperature by the temperature sensing element. Test transport of containerized potatoes and lemons guided the way to improvements in the MCC design for raising the performance characteristics of MCCs in their full-scale production.

NOTATION

G_a, air flow, kg/h; M, mass, kg; q_{br}, specific breathing heat, W/kg; c, heat capacity, kJ/(kg·K); q, heat release of 1 kg of raw material at the transport temperature, W/kg; t, temperature, ^{o}C; D, natural loss of freight (drying loss), %/day; λ, thermal conductivity, W/(m·K); φ, relative air humidity, %. Indices: fr, freight; 1, air entering into the freight; 2, air leaving the freight; 0, at T = 273.15 K; p, isobaric; a, air; out, outdoor; sc, scavenging.

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