A TURBO MODEL FOR PRODUCT CONDITIONS IN STORAGE AND TRANSPORT

H. F. Th. Meffert[1], J. W. Rudolphij[1], G. van Beek[2], L. M. M. Tijskens[2]
[1]Wageningen
[2]ATO-DLO, POBox 17, 6700 AA Wageningen, The Netherlands
E-mail g.vanbeek@ato.dlo.nl

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Abstract

A suitable model for the conditioning of products in refrigerated spaces is a crucial counterpart to quality change models for the prediction of quality and safety of perishable commodities in supply chains. Useful model concepts must relate design and operational factors with product conditions, of which temperature is the most important single factor. The model must be acceptable in the triangle of equipment owner-builder-user, not to forget inspectors and other competent authorities. Temperature range and distribution is a common basic information.

User-friendly dedicated models, theoretically sound, calibrated and validated by independent experimental work, using meaningful parameters linked to design and operation, are necessary to demonstrate the power of modelling to potential users. Fast response is an obligatory requirement for practical use. Accuracy becomes more important for research purposes. At the hand of an improved computational model, the advantages of a simplified engineering approach are demonstrated.

Introduction

Predicting Quality Change in conditioned chains for perishable commodities of agricultural origin, as well as of products of the food industry, has attained growing attention of Research Institutions and Fund Providers. Especially Predictive Microbiology has attracted the interest of public and private funds providers. The product temperature range is a yardstick for the quality of conditioning processes and equipment in storage and transport operations. Product temperature distribution is a prerequisite for the prediction of product quality development in Cold Chains, e.g. by stepwise convolution (Spiess 1988).

Temperature Range and Distribution

Temperature range

A mathematical model for the product temperature range under *static* conditions in refrigerated spaces, conditioned by circulating air, has been presented by Meffert (1992), and in a simplified version by Heap (1985). Based on the heat balance of an occupied refrigerated hold, a mechanistic model can be formulated on a physical-analytical base, which relates air and product temperature range with design and operational parameters.

The simple approach of the static cargo temperature range from the basic condition of constant delivery air temperature is strictly valid only for continuously modulating refrigeration power control downstream of the air cooler. This control mode is common in modern reefer transport equipment.

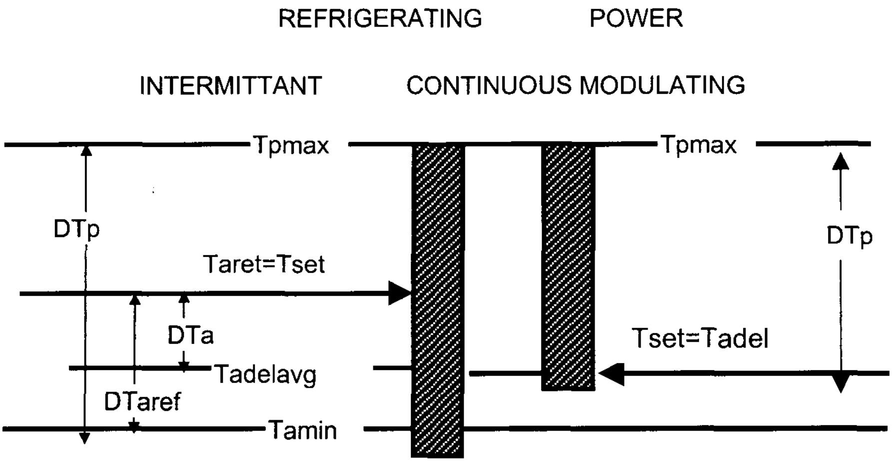

Figure 1 Air and cargo temperatures for continuous modulating/delivery air and stepwise/return air power / temperature control

Figure 1 depicts the relation of temperatures for the cases of intermittent, stepwise and continuous modulating control, and the heat-cool mode. Table 1 recapitulates the interrelation between the product temperature range and extreme temperatures for return air continuous modulation and delivery air stepwise control action of refrigeration appliances.

Table 1 Interrelation of product temperature range and extreme temperatures, depending on control mode.

	Control mode	
	Return air/stepwise	Del. air/continuous
Prod.temp.range DT_p	$\frac{Q_{ref}+(CC-1)*(Q_e+Q_i)}{\Phi(c_p*\rho)}+DT_{pP}$	$\frac{CC*(Q_e+Q_i)}{\Phi(c_p*\rho)}+DT_{pP}$
Min.prod.temp. $T_{amin}=T_{pmin}$	$T_{ret}-\frac{Q_{ref}}{\Phi(c_p*\rho)}$ $T_{ret}=T_{set}$	$T_{del}=T_{set}$
Max.prod.temp. T_{pmax}	$T_{amin}+DT_p$ $T_{amin}=T_{set}-\frac{Q_{ref}}{\Phi(c_p*\rho}$	$T_{amin}+DT_p$

Preliminary values for the Configuration Coefficient could be calculated from published experimental data sets. Most data originate from transport experiments. Only very few data could be collected from storage experiments on cold store and retail display cabinet scale. The analysis of some 54 data sets of air and cargo temperatures in 20' ISO Reefer containers (Meffert, 1998) resulted in: $CC = DT_p/DT_a = 2.44 \pm 0.88$.

Table 2 Apparent Configuration Coefficient values for 20' Integral Reefer Containers, derived from experiments by Irving and Sharp (1976)

Configuration	Config. Coeff. mean	Config. Coeff. range	Nr. of data sets
Register stack ¹)	2.6	1.9-3.6	4
Large back space	4.0		1
floor prof. open	3.2	2.9-3.6	3
floor prof. close	2.1	2.0-2.1	2
Off-set	2.6	2.5-2.6	2

¹) 2 containers, 2 packs

Experimental values for a 13.6 m long refrigerated semi trailer (Bennahmias and Labonne, 1993) and containers (Bennahmias 1985) with palletized cargo show values of 3 to 3.5. A CC-value of 2.5, therefore, appears a reasonable first approach for unspecified stacking patterns. With specific stacking patterns lower values can be reached, open profile ends, large back spaces and unitized cargoes tend to higher CC-values (table 2). CC-values for storage applications can be of a larger order. CCs of retail display cabinets range are of comparable magnitude, see table 3.

Table 3 Preliminary apparent Configuration Coefficients for storage and retail applications.

Application	CC	Nr. of sets	Ref.
Storage	1.6-14.1	6	Meffert 1992
Transport			
20' Reefer	2.43 ± 0.8	36	Meffert 1998
larger equipm.	3.0; 3.5	2	
Retail			
Island	2.3	1	
Multideck	2.11 ± 0.53 (1.4-3.2)	22	Meffert 1998

Temperature Distribution

The results of multipoint measurements in a three-dimensional product temperature field can be described by the Weibull Distribution Function for the occurrence of rare events.

$$F = 1 - \exp\left(-\left(\frac{X - Xo}{SCP}\right)^{SHP}\right)$$

The exponential function can be modelled by a Scale (SCP) and a Shape parameter (SHP), and is positioned by a finite minimum, the Location Parameter (Xo). Variation of the parameters allows the presentation of a wide range of distributions.

For constant air delivery temperature, the agreement of the measured product temperature distribution with a Weibull Distribution Function is obvious (Amos and Sharp 1998). For constant air return temperatures the distribution seems to approach the normal (Gaussian) distribution. However, the Weibull distribution function is able to cover this condition, too, with appropriate parameters. Experimental verification appears difficult because of the temperature variations of the fraction of the cargo close to the air delivery. From 35 experimental data sets values of the Weibull parameters could be calculated, which show a relation between SCP and DTa (Meffert, 1995):

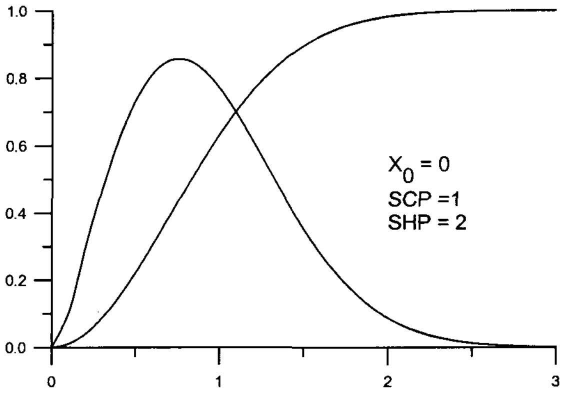

Figure 2 Weibull Distribution F (continuous from 0 to 1) and the probability density function (10x in y-direction).

$SCP/DT_a = 0.79 \pm 0.27$ and $SHP = 1.76 \pm 0.64$

The regression coefficient between the measured temperature distributions and the Weibull Distribution Function of the 35 data sets was at average 0.9916 ± 0.0092. Thus, in the average case, ca. 78 % of the cargo are within 1 DTa, 99.4 % within 2 DTa and 99.997 % within 3 DTa. As a preliminary general approach, parameter values can be suggested for continuous modulating air delivery temperature control:

Location Parameter:	$LP = T_0 = T_{amin} = T_{set}$
Scale Parameter:	$SCP = 0.80 * DT_a$
Shape Parameter:	$SHP = 1.75$

The recommended values indicate that ca. 77 % of the cargo are within 1 DTa, 99.3 % within 2 DTa and 99.996 % within 3 DTa, which means that 1/25000, 2 dm^3 of a 50 m^3 load may exceed $T_0 + 3DT_a$.

Computational Approach

The obvious problems of full scale experiments have aroused a search for relevant computational approaches. Simple and sophisticated computer programs have been designed for whole systems, refrigerated storage rooms, and transport equipment, road vehicles and reefer containers, and for partial systems like pallet configurations and stacking patterns. These programs need elaborate input procedures and need extensive computational facilities respectively computing time allowances.

An early computer program (Meffert and Van Beek 1983, 1988), was based on an engineering approach, designed for a quick evaluation of the effects of design and operational factors on the air and product temperature range. The Configuration Coefficient is a direct result. The model could be validated for Reefer Containers by comparison with experimental data sets, for the air distribution by Irving and Sharp (1976), for the temperature distribution by Van Nieuwenhuizen (1984). Primarily developed for Reefer containers, trucks and trailers, the approach is also applicable to display cabinets, storage rooms and reefer ship holds.

Possible ways to calculate the temperature distribution in refrigerated holds by a more complex computer model are offered by Comini et al. (1995), using FEM for heat transfer, to be combined with an appropriate introduction of the air distribution. Corroboration of the empirical-statistical approach by a theoretical-computational model would support the acceptance of the statistical model.

Model update

The development of knowledge, computational facilities, experimental instrumentation, and enforcement of stricter product temperature requirements on a legal or contractual base plead for improvement of the early model. Consideration of the dynamic pressure differences as additional moving forces in the air circulation system would have spoiled the major advantage of the program. A finer mesh can be applied on the load elements, to determine the 3-D temperature distribution in a unit load which is in accordance with the statistical application. Combination with the FEM approach of Comini et al. appears possible in a later stage, but this again leads further in the dilemma of greater computer facilities or longer computation times.

The model is available in VISUAL BASIC. It is useful for the quick calculation of product temperature ranges under steady conditions, which is sufficient for the evaluation of maximum product temperatures (which has to be detected) related to a volume fraction (which has to be prescribed). This procedure yields a Configuration Coefficient, related to design and operational factors. By variation of the input variables a factor analysis can be produced, which indicates the relative impact of the factors on the temperature range.

Discussion

Temperature range

Qualification of the influence of design and operational factors appears acceptable for design purposes. The same holds for operational questions, such as stowage patterns and the choice of equipment settings. Simple computer software is required for such purposes, with user-friendly input procedures and fast response.

Also for the evaluation of energy efficiency the accuracy might be sufficient. However, more elaborate input procedures and time consuming computations are no principal obstacles for such calculations on design level.

Temperature distribution

Assessment of the influence of temperature distributions on Quality Change, requires more accurate tools, which render product temperatures in tenth of a degree. Complex computations, again, are not prohibitive, on a strategic level and for research purposes. But they are in need of as accurate as possible operational and design parameters.

The more elaborate approaches are also necessary to test the simplifications. Both have to be validated by dedicated experiments, which need model guidance, ample instrumentation and time. A validated computer model could promote theoretical research.

General

In principle, the updated model is able to serve both purposes, calculation of temperature range and temperature distribution reasonably fast. However, a higher degree of resolution of the temperature field leads to a multiplication of computation time.

Resolution of the temperature field is an important point, for measurement, as well as for interpretation of experimental results. Mostly central pack temperatures are recorded, and can be used for the determination of the Weibull parameters. This means that for a 20' ISO Reefer container a volume fraction of 10 to 20 dm^3 is required, resolution in the order 1/1000 is required, in reverse proportional to the volume of the cargo. For extreme conditions, the volume fraction should rather be 1 dm^3, equal to a resolution of 1/20000. This does cause more difficulties for measurement than for calculation.

Refinement of the engineering model needs computer assistance, especially for the description of the air distribution. A generic model is wanted for testing of simplifications and exploration of the limits of application of the engineering model.

A quite different approach is suggested by Van der Sman (1997). However, the proposed LGA (Lattice Gas Automata) model is still in the state of development and not yet operational for the purpose of relating 3-D air flow and product temperatures in refrigerated holds, although it deserves attention in the longer run.

Conclusions

Experimental and computational research on the relation of air and product temperature in refrigerated holds is necessary to guide temperature monitoring and Quality Change prediction in cold chains.

Although based only on a restricted number of experiments, the updated engineering model has its value for the quick prediction of product temperature conditions in refrigerated holds.

The engineering model, a combination of the Kirchhoff Network approach for air distribution in occupied holds and a mean value thermal model, yields useful qualitative information on air and product temperature ranges, depending on heat load and air circulation. Configuration Coefficients can be predicted. Factor analyses can be performed with little additional effort.

Temperature distribution for Quality Change prediction needs a more complex and detailed model to cope with the necessary resolution of the temperature field. Such a model is as well needed for testing and further development, respectively limitation of the engineering model. Elements for refinement are presented by Moureh et. al. (1995), Comini et. al. (1995), and Lindquist (1998). However, extensions and refinement lead inevitable to more elaborate and computer time consuming procedures respectively extended workstations.

The available means allow the prediction of the product temperature range and distribution by producing Temperature Distribution Tables (TDT's), which should be applied for the qualification of transport and storage conditioning equipment and processes. TDT's should be accepted as an element in contracts for between suppliers and users of storage and transport services. Strategic research is necessary to clarify doubtful parts of TDT's, to improve existing models and to run validation experiments.

Recommendations

Dedicated validation experiments, necessary for the evaluation of models for various purposes and different computational requirements, should be undertaken in cooperation between research and industry, to establish the range of validity of developed models.

The application of the simple mechanistic model for product temperature range and distribution should further be explored experimentally and by computer modelling.

Temperature distributions in larger objects, Reefer containers, storage rooms, and smaller objects (retail cabinets) should be investigated. Generic user-friendly computational approaches to modelling of temperature fields should have more interest of research establishments and contractors from industry and government, especially those related to temperature monitoring and Quality Change prediction in storage and transport. Because of the necessity of equipment, manpower and time intensive full scale experiments, guidance by computer modelling is highly wanted.

Prepare Temperature Distribution Tables (TDTs) of products in storage and transport. These TDTs, produce data for equipment, conditioning, stacking, product, package and ambient conditions as parameters, in terms of standard range and distributions within the deviation of the parameters.

Nomenclature

CC	Configuration Coefficient	for Qi=0
CC'	Apparent Configuration Coefficient (as measured)	-
$c_p{}^*\rho$	Spec. heat per volume	Wh/m^3K
DT_a	Range of temperatures in the circulating air	K
DT_{ref}	Temperature difference imposed by the Reefer Unit	K
DT_p	Range of product temperatures	K
DT_{pP}	Overtemp. in heat generating bodies	K
Φ	Air circulation	m^3/h
F	Distribution	-
K	K-value of vehicle	W/m^2K
k_P	Heat transm. coefficient pack	W/m^2K
l	Therm. conductivity product in pack	W/mK
N	Shape Factor	-
$Q_e=U(T_e-T_i)$	External heat load	W
Q_i	Internal heat load	W
U =K*S	Heat load factor	W/K
S	Surface of insulated hold	m^3/h
$T_{adel(mean)}$	(Mean) delivery air temperature	°C
T_{aret}	Return air temperature	°C
T_e	External temperature	°C
T_i	Internal temperature	°C
T_{pmax}	Maximum product temperature	°C
T_{pmin}	Minimum product temperature	°C
T_{set}	Temperature control set point	°C
V	Volume of cargo	m^3
X	Characteristic (smallest) length of unit load	m
X	Independent variable in Weibull distribution	-

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