Journal of Environmental Management 119 (2013) 121–133

Contents lists available at SciVerse ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Thermodynamics of greenhouse systems for the northern latitudes: Analysis, evaluation and prospects for primary energy saving

Filip Bronchart [a], Michel De Paepe [b], Jo Dewulf [c], Eddie Schrevens [d], Peter Demeyer [a,*]

[a] The Institute for Agricultural and Fisheries Research (ILVO), Burg. van Gansberghelaan 115 bus 1, 9820 Merelbeke, Belgium
[b] Department of Flow, Heat and Combustion Mechanics, Ghent University (UGent), Sint-Pietersnieuwstraat 41, 9000 Gent, Belgium
[c] Research Group EnVOC, Ghent University (UGent), Coupure Links 653, 9000 Gent, Belgium
[d] Department of Biosystems, Katholieke Universiteit Leuven, Celestijnenlaan 200e, Box 2411, 3001 Heverlee, Belgium

A R T I C L E I N F O

Article history:
Received 30 January 2012
Received in revised form
7 January 2013
Accepted 11 January 2013
Available online 6 March 2013

Keywords:
Thermodynamics
Dehumidification
Vapour heat pump
Greenhouse
Exergy efficiency

A B S T R A C T

In Flanders and the Netherlands greenhouse production systems produce economically important quantities of vegetables, fruit and ornamentals. Indoor environmental control has resulted in high primary energy use. Until now, the research on saving primary energy in greenhouse systems has been mainly based on analysis of energy balances. However, according to the thermodynamic theory, an analysis based on the concept of exergy (free energy) and energy can result in new insights and primary energy savings. Therefore in this paper, we analyse the exergy and energy of various processes, inputs and outputs of a general greenhouse system. Also a total system analysis is then performed by linking the exergy analysis with a dynamic greenhouse climate growth simulation model. The exergy analysis indicates that some processes ("Sources") lie at the origin of several other processes, both destroying the exergy of primary energy inputs. The exergy destruction of these Sources is caused primarily by heat and vapour loss. Their impact can be compensated by exergy input from heating, solar radiation, or both. If the exergy destruction of these Sources is reduced, the necessary compensation can also be reduced. This can be accomplished through insulating the greenhouse and making the building more airtight. Other necessary Sources, namely transpiration and loss of CO_2, have a low exergy destruction compared to the other Sources. They are therefore the best candidate for "pump" technologies ("vapour heat pump" and "CO_2 pump") designed to have a low primary energy use. The combination of these proposed technologies results in an exergy efficient greenhouse with the highest primary energy savings. It can be concluded that exergy analyses add additional information compared to only energy analyses and it supports the development of primary energy efficient greenhouse systems.

1. Introduction

In Flanders (Belgium) and the Netherlands greenhouse production systems produce economically important quantities of vegetables, fruits and ornamentals (Bergen et al., 2010). The traditional greenhouse production system is comprised of a cover with high light transmittance and climate regulating devices such as heating, roof vents, CO_2 fertilization units, screens, and, in some cases, artificial lighting. Despite cold winter weather conditions (in Flanders the average January temperature is 3 °C), greenhouses are designed to provide an optimal indoor climate for year-round production of warm climate crops such as tomato, paprika and tropical ornamentals. In combination with automated cultivation systems, greenhouse structures make these crops profitable to cultivate year-round.

However greenhouse climate control has led to high primary energy use (1500 MJ/m^2/year in the Netherlands; Bakker, 2009). This results in greenhouse crops that use 30–40 times more primary energy than the energy of the crop itself. This very high primary energy use challenges the economic and environmental sustainability of traditional greenhouse systems. Therefore greenhouse systems need to be developed that still allow high crop yields while reducing primary energy use an order of magnitude lower than that of the traditional systems. Institutional research and development projects in the Netherlands and Flanders have started to work towards this goal.

A decade ago, a research and development project started in the Netherlands under the name "Greenhouse as Energy Source" (Bakker, 2009). This project was based on the hypothesis that the

* Corresponding author. Tel.: +32 9 2722764; fax: +32 9 2722801.
E-mail addresses: filip.bronchart@ilvo.vlaanderen.be (F. Bronchart), Michel.DePaepe@Ugent.be (M. De Paepe), jo.dewulf@Ugent.be (J. Dewulf), eddie.schrevens@biw.kuleuven.be (E. Schrevens), peter.demeyer@ilvo.vlaanderen.be (P. Demeyer).

0301-4797/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jenvman.2013.01.013

excess of heat in the greenhouse that enters during summertime by solar radiation could be captured using closed greenhouse environments and reused during the winter or as otherwise needed. To further develop this idea, an international contest called "Energy producing greenhouses" was started in 2005. This led to the construction of 3 prototype greenhouses in the research and development centre of Bleiswijk in the Netherlands. These research projects resulted in "Het nieuwe telen" (the new way of growing) with nearly 50% primary energy savings. About half of these savings are due to better insulation and dehumidification of the greenhouse. The other half is accomplished by using heat pumps combined with aquifer storage (Kasalsenergiebron, 2009). Unfortunately, heat pumps combined with aquifer storage are not economically feasible, despite 40% governmental support (Ruijs et al., 2010). Only better insulation and dehumidification show real promise. This contrasts starkly with the civil building industry, where the passive building standard reaches energy saving rates of 90% for heating (Kaan and De Boer, 2006). Passive building is economically attractive, as indicated by recent market expansion.

The question then arises, "Is the current research on primary energy savings for greenhouses based on a holistic vision of the (in) efficiencies?" The theory of thermodynamics indicates that first law (enthalpy/energy) analysis and mass analysis (conservation of mass) are especially useful for climate, energy or mass transfer modelling. Exergy or availability analysis, on the other hand, reveals possibilities for more efficient primary energy use (Moran and Shapiro, 1998; Annamalai and Puri, 2002; Dewulf et al., 2008).

A summary of the literature (particularly review articles) on primary energy savings, dehumidification, and CO_2 enrichment (Supplementary material A) reveals that research has been almost all founded on first-law (enthalpy/energy) analysis or conservation of mass. Up to now, exergy or availability analysis has only been rudimentary. Only 2 authors address exergy: Van Liere (2003) focuses on obtaining more exergy-efficient heat or CO_2, and von Elsner (2008) describes using low exergy (26 °C) heat from a power station's cooling tower for heating a greenhouse. Through the lack of exergy analyses in greenhouse research, adapted solutions could not be proposed. Such solutions are more likely to result in significant primary energy savings through a better understanding of the dynamics.

The objective of this paper is to provide a complete, both exergy and enthalpy based, thermodynamic analysis of greenhouse systems. To do so, we have derived specific exergy equations. The thermodynamic analysis then leads to proposals for appropriate primary energy saving technologies to develop greenhouse systems with a low environmental impact.

2. Thermodynamic analysis

2.1. The first law

The first law of thermodynamics states that energy is conserved. The change of internal energy of a closed system (dU) is equal to the heat transferred to the system (dQ) minus the work (dW) done during a process by the system (Carter, 2001).

$$dU = dQ - dW \tag{1}$$

Enthalpy (H) is defined by:

$$H = U + pV \tag{2}$$

With p the pressure and V the volume of the defined system.

For analysis, an energy balance is calculated for an open system (Fig. 1) with well-defined boundaries and different inputs and outputs.

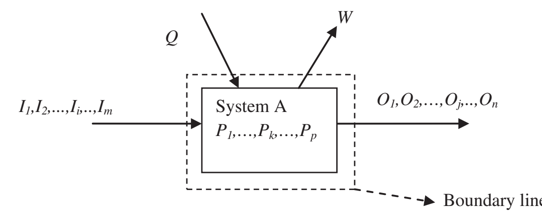

Fig. 1. Schematic presentation of an open system with inputs (I_i), outputs (O_j) and processes inside the system (p_k). Q is the heat delivered to the system and W the work delivered by the system.

In case of negligible potential and kinetic energy differences, the first law then gives (Moran and Shapiro, 1998):

$$\Delta U_A = Q - W + \sum_{i=1}^{m} H_{Ii} - \sum_{j=1}^{n} H_{Oj} \tag{3}$$

It is important to remember that in an open system the inputs and outputs of the energy balance are enthalpy values due to configuration work.

2.2. The second law

The second law of thermodynamics states that different energy forms are not freely interchangeable. As a consequence, the entropy of a closed adiabatic system A (S_A) undergoing an irreversible process increases and is unaltered for a reversible process (Carter, 2001).

$$\Delta S_A \geq 0 \tag{4}$$

Entropy (J/K) is calculated from the entropy difference. The entropy change of a closed system under a reversible process is its acquired heat (Q) divided by its temperature (in K) (without other processes in the system).

$$dS = \frac{dQ}{T} \tag{5}$$

In combination with the first law (1), this gives the "$T\,dS$" equation:

$$T\,dS = dU + p\,dV \tag{6}$$

From this last equation, the entropy change for an ideal gas between 2 states can be derived:

$$S_2 - S_1 = n \cdot \frac{c_p}{n} \cdot \ln\left(\frac{T_2}{T_1}\right) - n \cdot R \cdot \ln\left(\frac{p_2}{p_1}\right) \tag{7}$$

With c_p/n the heat capacity per mol (J/mol/K), n the number of moles, R the ideal gas constant (8.314 J/mol/K).

This equation indicates the similarity between the temperature and the pressure effect on the entropy change of an ideal gas.

2.3. Exergy

The exergy of a system is by definition the maximum work produced by the system and its surroundings when moving towards equilibrium with the environment (the dead state). The properties of the system at the dead state are defined by the outside temperature (T_e) and outside pressure (p_e). For atmospheric gases the reference environment has the atmospheric composition and pressures. For other species, chemical potential equations or reference environments are used (e.g. Szargut et al., 1988).