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The controllability assessment of flowsheeting options involving parallel-flow dryers

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Abstract

Models of parallel-flow (cocurrent and countercurrent) dryers have been developed within a steady-state process flowsheeting package (ASPENplus®) and applied to a case study involving a countercurrent timber veneer dryer to evaluate the ease of control for arrangements which include the use of recycle or a heat exchanger at the dryer exit to preheat the incoming air. The technique involves interfacing FORTRAN models, which allow both dynamic and steady-state analyses to be performed, with the ASPENplus® package. These FORTRAN models may also be called from the SPEEDUP® package, but in this case only the steady-state behaviour has been studied in ASPENplus® by running the unsteady-state analyses to steady state using a false time-stepping technique. For the case study of the countercurrent timber veneer dryer, the use of a heat exchanger is predicted to require 13% less fuel gas than no recycle and 6% less than the use of 30% outlet gas recycle at the optimum operating condition (minimum fuel gas use) for each system. The system is also predicted to be easier to control with a heat exchanger than with recycle, according to the Relative Gain Arrays for the systems studied. For the countercurrent veneer dryer, the use of 30% outlet gas recycle increases the outlet solids temperature compared with cases both with no recycle (corresponding to the dryer on its own) and with a heat exchanger between the outgoing and incoming gas, since recycle moves the operating region up the vapour pressure/temperature curve so that the sensitivities of both the outlet solids temperature and the outlet solids moisture content to the gas flowrate increase dramatically. This means that 30% recycle changes the preferred control pairings in this case from (solids outlet temperature, inlet air flowrate), (solids outlet moisture content, fuel gas flowrate) to (solids outlet temperature, fuel gas flowrate), (solids outlet moisture content, inlet air flowrate). The indicated pairings of controlled and manipulated variables differ with the amount of recycle, suggesting that dynamic analysis needs to be performed to assess the optimum control method for this system. © 1998 Elsevier Science S.A. All rights reserved.

Keywords: Flowsheeting; Parallel-flow dryers; Relative Gain Arrays

1. Introduction

There are some software packages [1–3] for the simulation of dryers and drying operations, but these packages are often self contained and stand-alone. This type of software is useful for the analysis of individual dryers, but such situations are rare, and it is normal to see dryers connected to heat exchangers, burners, condensers, cyclones, filters and other types of equipment. Stand-alone software is less helpful in such situations, where the dryer interacts with other items of equipment, and a flowsheeting approach is required. Also, the optimum operating condition for the dryer may not correspond to that for the process as a whole. The development of flowsheeting models of dryers in order to assess dryer controllability and to optimise dryer operation is also desirable because most flowsheeting packages already have built-in tools for assessing the ease of control and for optimisation.

Flowsheeting packages such as ASPENplus®, PROvision® and HYSYS® have been heavily developed for gas–liquid processing operations, but the evolution of such packages for solids processing operations has been less extensive. However, progress has been made on the optimisation of dryers, either as single units or as small sub-systems. Kaminski et al. [4] have demonstrated the optimisation of the operation of a fluidised bed dryer for processing the products of fermenting l-lysine where the overall objective function was a weighted average of several objective functions for product quality, energy consumption and final moisture content. The amount of weighting on each parameter was arbitrary, but the work demonstrated the effect of different choices on the optimum operating conditions. The optimal steady-state operation of batch dryers for sultana raisins [5] and other fruits

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[6] has also been explored, with the thermal energy consumption being minimised subject to constraints on the maximum product temperature. Other studies have concentrated on optimising the steady-state operation of dryers on their own, without considering recycle of outlet gases as an option or the effects of other plant items on the dryer [7–9].

Some reports of the dynamic simulation and control of individual drying units have been given [10–12], and a few of these studies, including that of a tunnel dryer used for processing grapes [13], have considered the use of recycle. However, these studies do not allow the interaction between the dryer and other processing operations to be assessed within commercial flowsheeting packages, although the drying modules in the work of Kiranoudis et al. [14,15] have been written as modular simulators which could be integrated in such schemes. Reports of progress towards the assessment and optimisation of dryers within larger flowsheeting packages have been scarce, but Yan and Rudolph [16] have modelled a fluidised bed gasifier for processing coal within ASPENplus® in the way that a dryer could be treated.

Recently, Marinos-Kouris et al. [17] have described the development of a new flowsheeting package for industrial dryers, since they felt that the dryer modules in existing flowsheeting packages are over-simplified and are based on poor understanding of the kinetics, that the database of solids properties is too limited in existing packages, and that the assessment of the economics is not sufficiently straightforward.

It is not clear why the use of user-defined modules for dryers within the existing packages cannot substantially cover many of these problems, and some of these issues, particularly the use of drying modules based on the use of characteristic drying curves with realistic solids properties, are addressed in this work. The use of user-defined modules for a countercurrent dryer in a simple assessment of process controllability within an ASPENplus® flowsheet based on a steady-state model is illustrated here. One of the limitations of this approach is that steady-state simulations do not allow the dynamic behaviour of process plant to be simulated without significant modification and extension to the process simulation package.

2. Simple controllability assessment for parallel-flow dryers

2.1. Theory

Dryers in which the gas and solids move in parallel to each other are common, with examples including belt conveyor and pneumatic conveying dryers. The flow path of gas and solids in these dryers enables them to be modelled as a series of control volumes, all linked together to form the whole dryer (Fig. 1). In addition, the axial mixing in these types of dryers is often small, and the solids and the gas have been assumed here to move through the dryer in plug flow. Heat and mass balances may be performed over each control volume, using the outlet conditions of the preceding control volume to define the inputs to the following control volume, as described in the following sections. The same control volumes may be linked together in different ways to simulate cocurrent and countercurrent dryers. The following control-volume mass and energy balances over small sections of the dryer have been given in more detail previously by Wang et al. [18], and only the most important steps are given here.

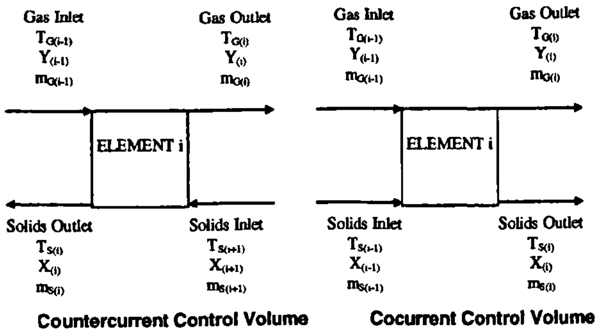

Fig. 1. Control volumes for different dryer layouts.

2.1.1. Control volume mass balances

Each control volume has been labelled as shown in Fig. 1. The mass balances over the control volume i may be written for each component entering and leaving the control volume, i.e., for solids, the moisture attached to the solids, the gas and the moisture in the gas. The solids passing through control volume i will be considered first.

2.1.1.1. Solids mass balance

The accumulation of solids mass within the control volume is the difference between the rates of input and output of solids, as follows (for a countercurrent dryer):

$$\frac{\mathrm{d}M_{s(i)}}{\mathrm{d}t}=m_{s(i+1)}-m_{s(i)} \tag{1}$$

where the symbols are described in the nomenclature list.

2.1.1.2. Solids moisture mass balance

For steady-state flow of solids into the dryer, the mass of dry solids within each control volume of the dryer is constant, and the unsteady-state mass balances for the amount of moisture in each control volume can be written as follows (for a countercurrent dryer):

$$\frac{\mathrm{d}(M_{s(i)}X_{(i)})}{\mathrm{d}t}=m_{s(i+1)}X_{(i+1)}-m_{s(i)}X_{(i)}+M_{s(i)}V_{(i)} \tag{2}$$

It is important to distinguish between the local drying rate of the solids ($V_{(i)}$, a negative term if the moisture content is decreasing) and the rate of change of the moisture content in each control volume of the dryer ($\mathrm{d}X_{(i)}/\mathrm{d}t$), since this last parameter depends on both the drying rate of the solids and the flowrates of moisture into and out of the control volume.

At steady state, the local drying rate will have a non-zero value, since the solids will still be drying, but $dX_{(i)}/dt$ is zero at steady state. Corresponding equations to Eqs. (1) and (2) are used for the gas phase.

Energy balances will now be described over the control volume.

2.1.2. Control volume energy balances

The energy content of a control volume will be the sum of the gas and solid phase contributions. In order to represent these expressions a reference state for water of liquid and an overall reference temperature of 0°C has been taken.

The enthalpy of the gas phase is due to the contribution of the dry gas and water vapour heat contents. This is expressed in the equation below, for a reference temperature of 0°C:

$$E_{G(i)}=(Cp_{G(i)}+Cp_{v(i)}Y_{(i)})T_{G(i)}+\lambda_{(i)}Y_{(i)} \tag{3}$$

The enthalpy of the solids phase will similarly be due to the contribution of the dry solids and liquid water enthalpies, as follows:

$$E_{s(i)}=(Cp_{s(i)}+Cp_{l(i)}X_{(i)})T_{s(i)} \tag{4}$$

The energy balance for the solid phase will now be presented.

2.1.2.1. Solids energy balance

The enthalpy of the solids within a control volume may be described by the equation below:

$$\begin{aligned}&(\text{rate of change of solids enthalpy})\\&\quad=(\text{solids enthalpy in})-(\text{solids enthalpy out})\\&\qquad+(\textit{enthalpy flow to and from gas})\end{aligned} \tag{5}$$

Setting a reference temperature of 0°C and rearranging gives, for a countercurrent dryer:

$$\begin{aligned}&M_{s(i)}\frac{dE_{s(i)}}{dt}\\&\quad=[m_{s(i+1)}(Cp_{s(i+1)}+Cp_{l(i+1)}X_{(i+1)})T_{s(i+1)}]\\&\qquad-[m_{s(i)}(Cp_{s(i)}+Cp_{l(i)}X_{(i)})T_{s(i)}]\\&\qquad+M_{s(i)}(Cp_{l(i)}T_{s(i)}V_{(i)}+Cp_{s(i)}J_{(i)})\end{aligned} \tag{6}$$

The third term in Eq. (6) includes the combined effects of latent energy loss due to vaporisation of moisture into the gas, the energy gained by the solids from the gas due to convective heat transfer, and sensible energy loss due to moisture transfer into the gas.

A similar expression for the gas-phase energy balance is used, since the solids and gas-phase energy balances are interlinked. The way in which the drying rate may be estimated for solids in a control volume will now be examined.

2.1.3. Drying rate

In general, the most appropriate model for the drying kinetic behaviour of a given material must be determined by experimental testing. A simple drying model is the concept of a characteristic drying curve, where the drying rate is related to the maximum drying rate when the solid offers no effective resistance to moisture movement. The drying rate (V) at any moisture content is related to this maximum by a function f such that:

$$V=-V_{max}\cdot f \tag{7}$$

There is a negative sign in this equation because the drying rate is a negative quantity (the moisture content of solids decreases as they dry). With this concept, the relative drying rate (f) is assumed to be a unique function of the characteristic moisture content (φ), where φ is defined by:

$$\varphi=\frac{X-X_e}{X_{cr}-X_e} \tag{8}$$

The 'critical point' (X_{cr}) is the moisture content above which drying is unhindered and the drying rate depends solely on the rate of heat transfer to the material. Some materials, including many foodstuffs and agricultural products, do not show 'critical points' and hindered drying starts immediately. Where the drying kinetics are unknown, it is common to assume that first-order kinetics apply, giving a linear falling-rate curve:

$$f=\varphi \tag{9}$$

Here, we treat the solids as non-hygroscopic, for simplicity. Including the hygroscopic nature of the material would require an expression for the equilibrium moisture content as a function of the local gas temperature and humidity. The maximum drying rate (V_{max}) may be estimated from the following equation:

$$V_{max}=\frac{\beta\cdot\phi_m\cdot(Y_W-Y)}{\rho_s\cdot x} \tag{10}$$

The Chilton–Colburn analogy is used to describe the relationship between the heat (h) and mass (β) transfer coefficients, giving:

$$V=-\left(\frac{h}{\rho_s\cdot x}\right)\cdot f\cdot\left[\frac{(Y_W-Y)}{Cp_y}\right] \tag{11}$$

The estimation of the heat-transfer rate to the solids will now be presented.

2.1.4. Heat transfer rate

A heat balance around the solids gives the following expression for the rate of change in the solids temperature (J):

$$J=\frac{1}{Cp_s}\cdot\left[\left(\frac{h\cdot\phi_H}{\rho_s\cdot x}\right)\cdot(T_G-T_s)+\lambda\cdot V\right] \tag{12}$$

The heat-transfer coefficient (h) has been estimated from standard correlations for heat-transfer coefficients [19].

2.2. Solution procedure

In previous work [19], the differential equations expressing the unsteady-state mass and energy balances and the kinetic expressions have been written within FORTRAN code which has been attached to the SPEEDUP® package, since this package allows such attachments to be made easily, and the package is well suited to the use of FORTRAN code. This arrangement allows the model to be transferred to other FORTRAN-based packages (such as ASPENplus®), even when these packages are steady-state ones. Many of these packages are sequential-modular ones, as opposed to the equation-orientated approach of SPEEDUP®, but they still allow FORTRAN code to be included as user-defined unit operations models. In the SPEEDUP® model, the differential equations for dryers are included in the FORTRAN code, and this code may be accessed by any other program. An interface has been written, in the form of a user-defined USER unit operation model in ASPENplus®, which takes these differential equations and handles them as described below.

(1) ASPENplus® sends the inputs to the dryer module in the user-defined USER unit operation model.

(2) Within the user-defined USER unit operation model, which includes the FORTRAN code originally used in the SPEEDUP® package, the states of the system (gas and solids temperature, gas humidity and solids moisture content) within all the elements of the dryer are guessed as being equal to the inlet values.

(3) The inlet values are held constant, while the differential equations for the states in the elements are integrated by a subroutine within the user-defined USER unit operation model until the rate of change of each of the states is small (moisture content and humidity changes of less than 10^{-6} $\mathrm{kg^{-1}\ s^{-1}}$, temperature changes of less than $10^{-2}\ \mathrm{K\ s^{-1}}$). This procedure is equivalent to running the equipment until steady state is achieved.

(4) These states are reported back to the ASPENplus® flowsheet from the user-defined USER unit operation model.

2.3. Simple measures of process controllability

2.3.1. Controlled, manipulated and disturbance variables

The main aim in a drying operation is to produce an end product which is of the required moisture content. However, a further control objective is often to keep the product temperature below a certain level. This requirement may be due to many reasons, including downstream processing requirements, or the need to limit the degradation of thermally sensitive materials. The steady state operation of a dryer may be subject to a number of disturbances, including changes in the inlet solids moisture content and inlet solids temperature which are often dictated by the operation conditions of upstream plant. Gas humidity also varies on a daily, weekly and seasonal basis.

In order to minimise the effect on the process of these disturbance variables, the operating conditions of the dryer must be manipulated. Typically, the two variables used to regulate the operation of a dryer are the inlet air flowrate and fuel gas flowrate.

2.3.2. Controllability assessment

The ease of control for a process may be estimated through the process Relative Gain Array (RGA) using a standard method [20]. An outline of the application of the RGA technique for the case of a drying system is given in the following section. This will be followed by a summary of some other simple measures of controllability. A common feature of all these measures is that they are based on the steady-state response of the system (open-loop). Open-loop controllability indicators have been reported on their own in recent years [21], since these indicators give a useful first estimate of the process plant layouts which are most promising for further control studies. No analysis of the dynamic response for any of the models has been carried out here.

2.3.2.1. Relative Gain Array (RGA) technique

The RGA technique involves representing the control system as a multi-input multi-output (MIMO) block. The two control variables (the solids outlet temperature T_{so} and the outlet moisture content X_o) may be represented as outputs, with the two manipulated variables (the inlet air flowrate m_{Gin} and the fuel gas flowrate m_f) as inputs.

If the process is linearised at the operating point in the following way

$$\delta\tilde{T}_{so}=\left(\frac{\partial\tilde{T}_{so}}{\partial\tilde{m}_{Gin}}\right)_{11}\delta\tilde{m}_{Gin}+\left(\frac{\partial\tilde{T}_{so}}{\partial\tilde{m}_f}\right)_{12}\delta\tilde{m}_f \qquad (13)$$

$$\delta\tilde{X}_o=\left(\frac{\partial\tilde{X}_o}{\partial\tilde{m}_{Gin}}\right)_{21}\delta\tilde{m}_{Gin}+\left(\frac{\partial\tilde{X}_o}{\partial\tilde{m}_f}\right)_{22}\delta\tilde{m}_f \qquad (14)$$

where the tildes represent deviation variables (from the steady-state operating point), then we can define the Process Gain Array Φ by

$$\Phi=\begin{pmatrix}\left(\frac{\partial\tilde{T}_{so}}{\partial\tilde{m}_{Gin}}\right)_{11} & \left(\frac{\partial\tilde{T}_{so}}{\partial\tilde{m}_f}\right)_{12}\\ \left(\frac{\partial\tilde{X}_o}{\partial\tilde{m}_{Gin}}\right)_{21} & \left(\frac{\partial\tilde{X}_o}{\partial\tilde{m}_{Gin}}\right)_{22}\end{pmatrix} \qquad (15)$$

and the RGA matrix Λ by

$$\Lambda=\Phi^{-1}*\Phi^{T} \qquad (16)$$

where * indicates an element by element product. The differentials of Eq. (15) may be assessed by linearising the model output about the current operating point and estimating the slopes of the response surfaces at that point. The quality of the linearisation used here has been checked, and the predicted change in the solids outlet temperature and moisture content from the linearised model for a 1% change in both inputs is within 0.5% of the predicted change from the com-

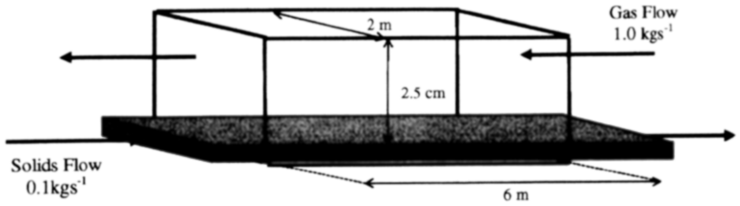

Fig. 2. Case study layout for parallel-flow dryer model.

plete, non-linearised, model given the same change in both inputs.

If the magnitudes of the off-diagonal elements of the RGA are greater than those of the diagonal ones then the system will be very interactive (manipulating one variable strongly affects both outputs) and hence more difficult to control. Also negative elements in the RGA indicate that the response of the output to the coupled input is reversed. Reverse response is undesirable since systems showing it are more difficult to control, and it is often an indicator of closed-loop instability. It is desirable to have pairings which are as close to unity as possible, since the control loops given by these pairings will only be slightly affected by other control loops.

2.3.2.2. Process Condition Number (C)

Bruns and Smith [22] suggested the use of a Process Condition Number (*C*) as another measure of controllability based on steady-state analysis. This number is obtained by decomposing the Process Gain Array using singular value decomposition to give a diagonal matrix of singular values. The Process Condition Number is defined as the ratio of the largest to the smallest singular values, and a relatively large value of the Process Condition Number indicates considerable interaction between the control loops. The Process Condition Number is the traditional algebraic definition of a condition number, applied here to the Process Gain Array, and it quantifies the degree of numerical difficulty in inverting a matrix. Since many process control techniques involve the use of matrix inversion either implicitly or explicitly, this measure is one which is appropriate for assessing the difficulty in controlling a process.

2.3.2.3. Morari Integral Controllability (MIC)

The Morari Indices of Integral Controllability (MIC) have been defined by Grosdidier et al. [23] as the eigenvalues of the Process Gain Array after it has been modified so that all diagonal elements are positive in sign. They showed that if the control system contains integral action, the system as a whole may be controlled if all eigenvalues of the modified Process Gain Array also have positive signs.

2.3.2.4. Niderlinski stability criterion (NI)

This criterion (NI) is the ratio of the determinant of the Process Gain Array to the product of the diagonal elements of the same matrix. Niderlinski [24] showed that a negative value of this criterion suggests that the system will be closed-loop unstable if all the controllers (for the pairings between controlled and manipulated variables) have positive loop gains and integral control action.

Table 1
Main parameters for the case study

Parameter	Symbol (units)	Value
Initial moisture content	X_{in} (kg kg^{-1})	1.35
Inlet humidity	Y_{in} (kg kg^{-1})	0.01
Outlet moisture content	X_o (kg kg^{-1})	0.15
Critical moisture content	X_{cr} (kg kg^{-1})	1.2
Inlet gas temperature	T_{Gin} (°C)	250
Inlet solids temperature	T_{sin} (°C)	50
Solids feedrate	m_{sin} (kg s^{-1})	0.1
Gas feedrate	m_{Gin} (kg s^{-1})	1.0
Solids density	ρ_s (kg m^{-3})	450
Board thickness	x (m)	0.0025

3. Case study

A case study for a parallel-flow dryer has been described in Langrish et al. [19] as an example of a countercurrent conveyor dryer used to season peeled timber veneers. The layout of the system is shown in Fig. 2. The principal parameters are listed in that work Table 1.

Flowsheet layouts for cases of 30% outlet air recycle (Fig. 3) and the use of a counterflow heat exchanger with a UA product of 200 W K^{-1} (Fig. 4) are given. The flowsheet layout for no recycle is the same as that for 30% recycle, but the flowrate through the recycle loop is zero in the case of no recycle. Minimising the fuel gas flowrate has been the input objective function used in the optimisation, which has been carried out using the standard Sequential Quadratic Programming technique available in ASPENplus™. The recycle ratio of 30% is a typical value, while the UA product of 200 W K^{-1} is an estimate based on an exchanger of 1 m^2 area with an overall heat-transfer coefficient of 200 W m^{-2} K^{-1}.

4. Results and discussion

4.1. Process controllability in countercurrent operation: different recycle schemes

The gas inlet temperature for the dryer was constrained to be below 400°C, and this constraint was active for all the

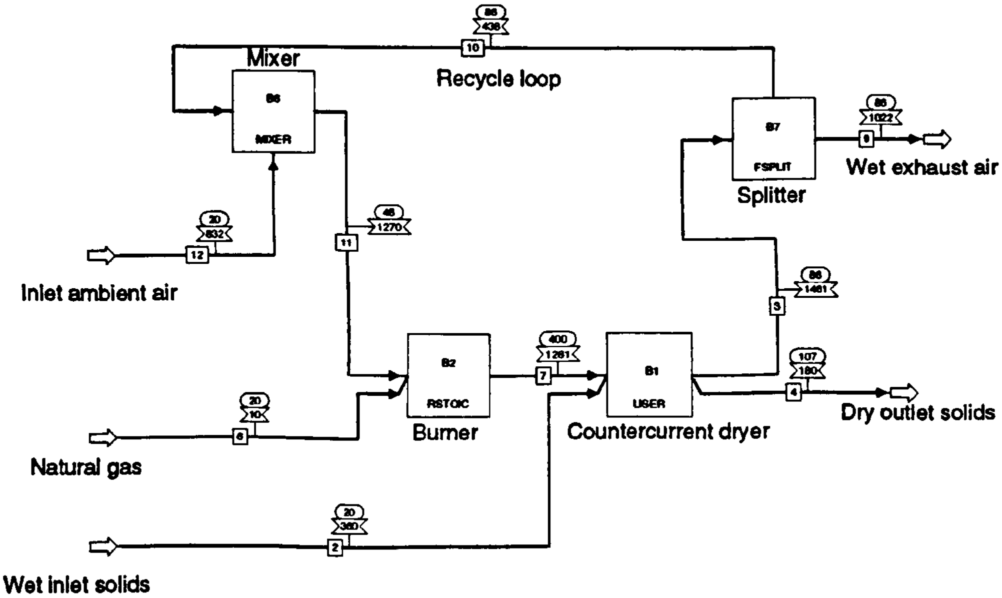

Fig. 3. Flowsheet layout for recycle case.

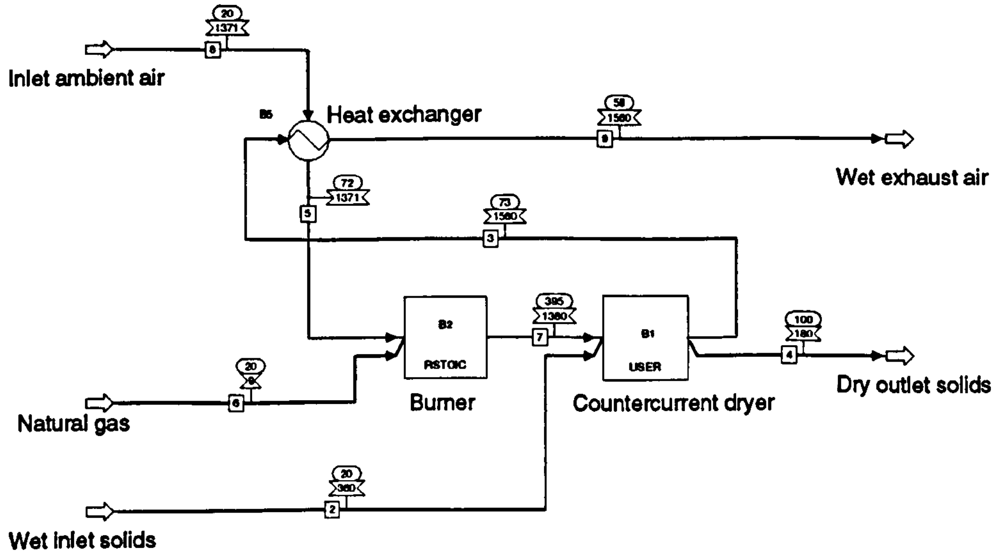

Fig. 4. Flowsheet layout for heat exchanger case.

flowsheets assessed. This agrees with the analytical solution for ideal heat demand by Keey [25], who demonstrates that the minimum heat requirement for a drying process occurs at the highest tolerable gas inlet temperature. The Relative Gain Array (RGA) and other steady-state criteria are given in Table 2.

In all cases, the Process Gain Array has the following features. As the air flowrate increases with a constant fuel gas flowrate, the temperature of the inlet air decreases, so the temperature of the outlet solids (with which the inlet air is in closest contact) also decreases ($\partial \bar{T}_{so}/\partial \tilde{m}_{Gin}$ is negative). The drying rate is reduced (and hence the outlet moisture content is increased) by an increase in the air flowrate through the dryer ($\partial \tilde{X}_o/\partial \tilde{m}_{Gin}$ is positive), since the decrease in air inlet temperature is not fully compensated for by the increase in heat-transfer coefficients. The effect of decreasing the fuel gas flowrate at constant air flowrate is similar to that of increasing the air flowrate at constant fuel gas flowrate.

For the cases of no recycle (corresponding to the use of the heat exchanger on its own) and the use of a heat exchanger, the Relative Gain Arrays suggest that the optimum pairings of controlled and manipulated variables are to control the solids outlet temperature by manipulating the inlet air flowrate, and similarly matching the solids outlet moisture content with the fuel gas flowrate, since the diagonal elements of the Relative Gain Arrays are larger than the off-diagonal ones. However, for the case of using recycle, the indicated pairings are different, with the off-diagonal elements being

Table 2
Steady state controllability study results for plug-flow dryers

	No recycle or heat exchanger	Recycle fraction 0.3	Heat exchanger
Minimum fuel gas flowrate (kg h^{-1})	10.9	10.2	9.5
Process Gain Array	$\begin{pmatrix} -0.035 & 21.0 \\ 4.53\times10^{-5} & -0.0672 \end{pmatrix}$	$\begin{pmatrix} -0.1325 & 18.6 \\ 5.01\times10^{-3} & -0.0633 \end{pmatrix}$	$\begin{pmatrix} -0.0275 & 36.4 \\ 2.3\times10^{-5} & -0.107 \end{pmatrix}$
Relative Gain Array	$\begin{pmatrix} 1.679 & -0.679 \\ -0.679 & 1.679 \end{pmatrix}$	$\begin{pmatrix} -9.06 & 10.06 \\ 10.06 & -9.06 \end{pmatrix}$	$\begin{pmatrix} 1.398 & -0.398 \\ -0.398 & 1.398 \end{pmatrix}$
Morari Indices of Controllability	$\begin{pmatrix} 0.0163 \\ 0.0859 \end{pmatrix}$	$\begin{pmatrix} -0.0046 \\ 0.2005 \end{pmatrix}$	$\begin{pmatrix} 0.0181 \\ 0.1164 \end{pmatrix}$
Process Condition Number	3.14×10^5	3.73×10^5	6.29×10^5
Niderlinski Stability Criterion	0.596	−0.110	0.716

greater than the diagonal ones, and here the preferred arrangement is to control the solids outlet temperature by manipulating the fuel gas flowrate, and similarly matching the solids outlet moisture content with the inlet air flowrate. The reason for this change in controller pairings is considered below.

Comparing the case of a 30% recycle fraction with the no recycle case, the beneficial effect of recycle in terms of saving fuel gas (energy) is small but significant (around 6%). As described by Keey [25], thermal economy in dryers can be improved by raising the temperature of the inlet air or by permitting a damper exhaust through increasing the recycle ratio. However, the case of 30% recycle is predicted to be more difficult to control, according to all the measures of controllability considered here, as well as leading to potential operational problems in extreme cases of higher recycle ratios, such as larger heat losses at higher temperatures and the formation of dew on cool surfaces when operating with a moister exhaust. The Process Condition Number is larger, and the magnitudes of the off-diagonal elements of the Relative Gain Array are greater than those of the diagonal ones. The Niderlinki Stability Criterion is negative for the recycle case, indicating that the system may be unstable for closed-loop control if all the controllers (for the pairings between the controlled and manipulated variables) have positive loop gains and integral control action. The Morari Indices of Controllability also suggest that the recycle case may be difficult to control with integral action since some of the eigenvalues of the modified Process Gain Array are negative.

In the case of recycle, the temperature and humidity of the outlet gas directly affect the inlet gas conditions to the dryer, and this effect may destabilise the dryer operation. The use of recycle, compared with the use of a heat exchanger, means that changes in the outlet gas humidity have an interactive effect on the dryer operation since they affect the inlet gas conditions. An important feature of the recycle case compared with that for no recycle is that the humidity of the air at the inlet of the dryer increases because of the recycled outlet gas. The wet-bulb temperature of the gas in the dryer rises because of the greater gas humidity, causing the outlet temperature of the solids to increase (from 100.8°C to 107.4°C predicted). This rise in solids temperature can be viewed as necessary to create the same vapour pressure driving force between the surface of the solids and the bulk gas, since the vapour pressure in the bulk gas increases with increasing inlet gas humidity. The increases in solids temperature and gas humidity have the effect of moving the operation up the vapour pressure/temperature curve so that the sensitivity of both the outlet solids temperature and the outlet solids moisture content to the gas flowrate is much larger. In the case of the sensitivity of the outlet solids temperature to the gas flowrate $(\partial\tilde{T}_{so}/\partial\tilde{m}_{Gin})$, this parameter is −0.035 for no recycle and −0.1325 for recycle, while the sensitivity of the outlet solids moisture content to the gas flowrate $(\partial\tilde{X}_o/\partial\tilde{m}_{Gin})$ is an order of magnitude higher for recycle (5×10^{-4}) compared with that for no recycle (4.5×10^{-5}). It is this latter change in magnitude which has the main impact on the Relative Gain Array, changing the preferred pairings of manipulated and controlled parameters from (inlet air flowrate, solids outlet temperature) and (fuel gas flowrate, solids outlet moisture content) for no recycle to (fuel gas flowrate, solids outlet temperature) and (inlet air flowrate, solids outlet moisture content) for 30% recycle. This change in the pairings of controlled and manipulated variables with different operating conditions (the amount of recycle) emphasises the need to extend this analysis to consider the system dynamics, in particular the actual closed-loop interaction. The change in the Relative Gain Array occurs once the recycle ratio reaches 30%, when the sensitivity of the outlet solids moisture content to the gas flowrate $(\partial\tilde{X}_o/\partial\tilde{m}_{Gin})$ increases by an order of magnitude compared with that for no recycle.

The lower operating cost involved in using a heat exchanger is not the only consideration addressed in this work. While using a heat exchanger at the outlet to recover thermal energy from the gas involves a significant capital cost, it also removes one of the feedback effects due to recycle, that due to the outlet gas humidity. The additional capital cost of a heat exchanger and the reduced operating cost of this option are both fairly straightforward points, but the improvement in the likely controllability of the process is possibly less clear. Unlike the recycle case, the Niderlinski

Stability Criterion is not negative, so the heat exchanger system should be easier to control in a closed-loop control system with normal positive gains and integral control action. For the Morari Indices of Controllability, there are no negative eigenvalues in the modified Process Gain Array. The off-diagonal elements of the Relative Gain Array for the heat-exchanger system are the smallest of all the systems considered, indicating fewer difficulties than the other systems with interactions between control loops. The large impact of the fuel gas rate on the outlet solids temperature (due to the outlet gas from the dryer being used to heat the air entering the dryer) means that the Process Condition Number is the largest of all the cases considered, but the other indicators of controllability indicate that the heat-exchanger system may have some advantages over the recycle scheme in terms of controllability, even though the capital cost will be greater. The reduction in required fuel gas flowrate compared with the case of no recycle is also larger (13%) than that for 30% recycle (6%), because the outlet gas, with its higher humidity, is not being mixed with the inlet gas, a situation which reduces the drying rates.

5. Conclusions

The use of dryer models within process simulation packages has been demonstrated for simple control studies on a countercurrent dryer for timber veneers and for a sensitivity study on a spray dryer. For the countercurrent veneer dryer, the use of 30% outlet gas recycle increases the outlet solids temperature compared with cases both with no recycle (corresponding to the dryer on its own) and with a heat exchanger between the outgoing and incoming gas, since recycle moves the operating region up the vapour pressure/temperature curve so that the sensitivities of both the outlet solids temperature and the outlet solids moisture content to the gas flowrate increase dramatically. This means that 30% recycle changes the preferred control pairings in this case from (solids outlet temperature, inlet air flowrate), (solids outlet moisture content, fuel gas flowrate) to (solids outlet temperature, fuel gas flowrate), (solids outlet moisture content, inlet air flowrate). The use of a heat exchanger is likely to give better thermal economy and improved controllability compared with the use of 30% outlet gas recycle, in spite of the higher capital cost when using a heat exchanger. This analysis of process control strategies based on steady-state analysis also highlights the effect of recycle ratio on the system performance. The effect of recycle ratio on the indicated pairing combination indicates the need to carry out further dynamic analysis for this system.

6. Nomenclature

A	surface area of heat exchanger, m^2
C	Process Condition Number
Cp	specific heat capacity, $J\ kg^{-1}\ K^{-1}$
E	enthalpy, $J\ kg^{-1}$
f	relative drying rate
h	heat-transfer coefficient, $W\ m^{-2}\ K^{-1}$
J	heating rate, $K\ s^{-1}$
k	thermal conductivity, $W\ m^{-1}\ K^{-1}$
L	length of veneer in dryer, m
m	mass flowrate, $kg\ s^{-1}$
MIC	Morari Indices of Integral Controllability
M	mass, kg
NI	Niderlinski Stability Criterion
Nu	Nusselt number
R	gas constant, 8.3144 $J\ mol^{-1}\ K^{-1}$
Re	Reynolds number
t	time, s
T	temperature, °C
u	average relative velocity between the gas and the solids in the control volume, $m\ s^{-1}$
U	overall heat-transfer coefficient, $W\ m^{-2}\ K^{-1}$
V	drying rate, $kg\ kg^{-1}\ s^{-1}$
x	board thickness, m
X	solids moisture content, $kg\ kg^{-1}$
Y	gas humidity, $kg\ kg^{-1}$

Greek

β	mass-transfer coefficient, $kg\ m^{-2}\ s^{-1}$
ϕ_H	Ackermann correction factor
ϕ_m	humidity-potential coefficient
Φ	Process Gain Array
φ	characteristic moisture content
λ	latent heat of vaporisation, $J\ kg^{-1}$
Λ	Relative Gain Array
μ	viscosity, $kg\ m^{-1}\ s^{-1}$
ρ	density, $kg\ m^{-3}$
σ	psychrometric coefficient

Subscripts

a	dry air
cr	critical
e	equilibrium
G	gas
i	element i
in	inlet
l	liquid
max	maximum
o	outlet
s	solids
S	wet solids
v	vapour
W	fully-wetted surface
y	humid gas

Superscripts

$\tilde{}$	deviation variable

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References

[1] Technical Engineering Applications, Winsteam 1.0a, Drying Technology, 12(5) (1994) 1239–1240.

[2] Z. Pakowski, dryPAK v1.1: program for psychrometric and drying computations, Drying Technol. 12 (7) (1994) 1765–1768.

[3] P.J.A.M. Kerkhof, F.G. Kieviet, Psychro 1.0 drying software, Drying Technol. 13 (4) (1995) 1033–1034.

[4] W. Kaminski, I. Zbicinski, S. Grabowski, C. Strumillo, Multiobjective optimisation of drying processes, Drying Technol. 7 (1989) 1–16.

[5] G.K. Vagenas, D. Marinos-Kouris, The design and optimisation of an industrial dryer for sultana raisins, Drying Technol. 9 (1991) 439–461.

[6] R. Bertin, M. Blazquez, Modelling and optimisation of a dryer, Drying Technol. 4 (1986) 45–66.

[7] J.R. Thygeson, E.D. Grossman, Optimization of a continuous through-circulation dryer, AIChE J. 16 (1970) 749–755.

[8] Y.K. Ahn, H.C. Chen, L.-T. Fan, G.G. Wan, Optimum design of a moving bed grain dryer by dynamic programming, Can. J. Chem. Eng. 42 (1964) 117–120.

[9] H.A. Becker, P.L. Douglas, S. Ilias, Development of optimization strategies for industrial grain dryer systems, Can. J. Chem. Eng. 62 (1984) 738–745.

[10] D. Platt, T.R. Rumsey, A. Palazoglu, Dynamic modelling of a cross flow rice dryer, Hilgardia 58 (4) (1990) 1–46.

[11] C.T. Kiranoudis, Z.B. Maroulis, D. Marinos-Kouris, Dynamic simulation and control of conveyor-belt dryers, Drying Technol. 12 (7) (1994) 1575–1603.

[12] R.Y. Jumah, A.S. Mujumdar, A PC program for preliminary study of a continuous well-mixed fluid bed dryer, Drying Technol. 11 (3) (1993) 831–846.

[13] C.T. Kiranoudis, Z.B. Maroulis, D. Marinos-Kouris, Modelling and optimization of a tunnel grape dryer, Drying Technol. 14 (7–8) (1996) 1695–1718.

[14] C.T. Kiranoudis, Z.B. Maroulis, D. Marinos-Kouris, Simulation of drying processes: an integrated computer-based approach, Chem. Eng. Res. Design 72 (1994) 307–315.

[15] C.T. Kiranoudis, Z.B. Maroulis, D. Marinos-Kouris, An integrated computer-based dryer simulator, Comput. Chem. Eng. 18(s) (1994) 265–269.

[16] H.M. Yan, V. Rudolph, ASPENplus based simulation of a compartmented fluidised bed gasifier process, Proc. Chemeca '95, Adelaide, 1995, 84–89.

[17] D. Marinos-Kouris, Z.B. Maroulis, C.T. Kiranoudis, Computer simulation of industrial dryers, Drying Technol. 14 (5) (1996) 971–1010.

[18] F.Y. Wang, I.T. Cameron, J.D. Litster, Further theoretical studies on rotary drying processes represented by distributed systems, Drying Technol. 13 (3) (1995) 737–751.

[19] T.A.G. Langrish, W.-F. Cao, A.C. Harvey, An evaluation of the comparative ease of operation and operating cost for cocurrent and countercurrent dryers, Proc. Sixth Australasian Heat and Mass Transfer Conference, Heat and Mass Transfer Australasia, Sydney, 1998, 435–442.

[20] G. Stephanopoulos, Chemical Process Control: An Introduction to Theory and Practice, Prentice Hall, NJ, 1984, 497–500.

[21] S. Skogestad, K. Havre, The use of RGA and condition number as robustness measures, Comput. Chem. Eng. 20(s) (1996) 1005–1010.

[22] D.D. Bruns, C.R. Smith, Singular value analysis: a geometrical structure for multivariable processes, AIChE Winter Meeting, Atlanta, 1982, 9–12.

[23] P. Grosdidier, M. Morari, B.R. Holt, Closed-loop properties from steady-state gain information, Ind. Eng. Chem. Fundam. 24 (1985) 221–235.

[24] A. Niderlinski, A heuristic approach to the design of linear multivariable systems, Automatica 7 (1971) 691–701.

[25] R.B. Keey, Drying of Loose and Particulate Materials, Hemisphere, New York, 1991, 261–266.