HEAT PUMP DEHUMIDIFIER DRYING TECHNOLOGY—STATUS, POTENTIAL AND PROSPECTS

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ABSTRACT

Dehumidifier drying is an enabling technology with unique potential benefits for drying high-quality temperature-sensitive products. Yet dehumidifier technology remains a niche player in the drying industry. The drying capacity of annual global sales is less than 0.5% of estimated global dried timber production, and dehumidifier drying of other products is largely limited to situations where the process offers special benefits. Compared with conventional dryers, many potential users view dehumidifier technology as fragile, slow and high capital cost on a per unit capacity basis.

While dehumidifier drying is unlikely to supplant conventional drying processes, research has demonstrated that it has the potential for significant growth. For such expansion, the industry needs to adopt a more integrated approach to dehumidifier technologies, taking into account the potential of: unique drying environments for new products and added value, high system efficiency and reliability, low environmental impact, and ease of use. To secure these benefits for their users the dehumidifier industry should promote good practices in dehumidifier applications, such as standard methods for rating capacity and efficiency, accepted performance benchmarks, and recommended drying schedules.

1. INTRODUCTION

Heat pump dehumidifier dryers have been in widespread commercial use since the 1970's, particularly in the timber and food drying industries. The purpose of this paper is to review the current development of this technology and examine the opportunities and barriers for market uptake. Critical issues facing dehumidifier technology will be discussed, including competition with alternative technologies. A case study is presented to illustrate the global potential for energy and greenhouse gas emission reductions through application of dehumidifier drying technology.

Heat pump dryers have a number of different configurations, depending on the placement of the heat pump evaporator. Figures 1–3 illustrate some of the options (Charters and Aye 1993). Here the open-ended arrows represent airflows taken from, or being discharged to, the local environment and the dashed line indicates the kiln boundary. Figure 1 is a type of heat-and-vent drier, based on classical dryer concepts, in which the heat source is provided a heat pump drawing heat from the surrounding atmosphere. Figure 2 shows a heat recovery heat pump drier, in which heat is recovered from moist kiln air as it is exhausted to the atmosphere. This is an example of an open system which takes advantage of the ability of the outdoor air to provide drying. This scheme is especially applicable in progressive driers, such as tunnel driers or deep bed driers, where the humidity of the air stream undergoes a substantial change in its passage through the product.

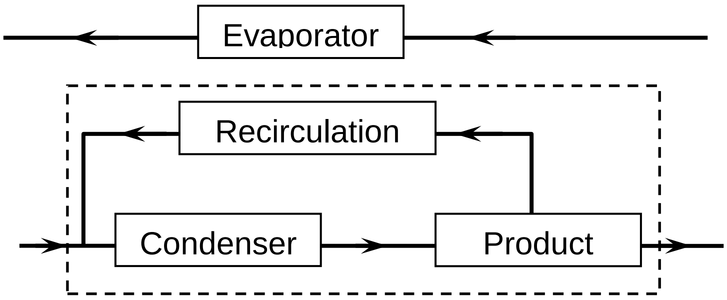

Figure 1. Atmospheric heat source heat pump drier.

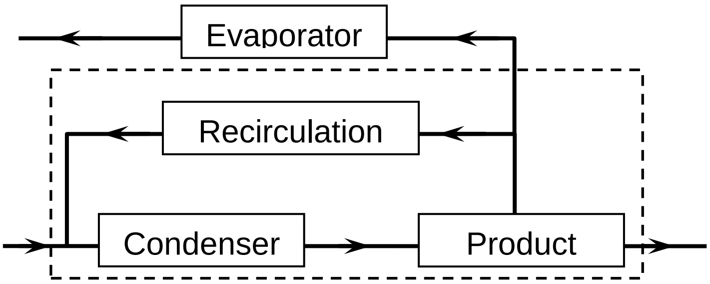

Figure 2. Open cycle heat pump drier with heat recovery.

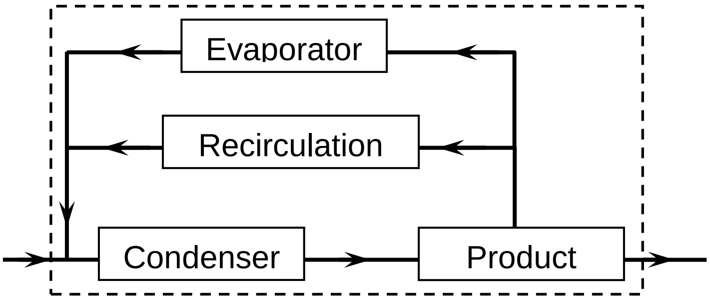

Figure 3. Schematic of a heat pump dehumidifier system which uses air venting for temperature control.

The configuration shown in Figure 3 is a dehumidifier. Although this configuration may be operated in a vented mode, with air being vented as required for temperature control, the environmental air state has only a weak influence on the operation if the system is well designed. Alternatively the dehumidifier kiln can be operated in a fully-closed non-vented mode, in which case an external heat exchanger is used to remove excess heat from the kiln chamber. A particular feature of fully-closed driers is that they provide a means to dry products in a controlled or modified atmosphere, which may be oxygen free. This paper focuses mainly, but not exclusively, on dehumidifier systems. We do not consider desiccant dryers, which are widely used for maintaining low dew-point drying environments where heat pump dehumidifier systems are not normally applicable.

2. STATUS OF DEHUMIDIFIER TECHNOLOGY

The apparent simplicity of the heat pump dehumidifier process is both a hindrance and an aid to the promulgation of the technology. The simplicity of the concept has encouraged the air-conditioning, refrigeration and kiln drying industries to promote the use of simple dehumidifier systems which fuelled a great deal of the expansion of the industry in the 1970s and 1980s. However, success rates amongst these installations were poor, providing a negative legacy for the industry.

The reason for the poor success is that heat pump dehumidifiers are applied in closed or semi-closed processes. In these processes, energy feedback leads to coupling between different loss mechanisms, creating novel design and operating challenges. Awareness and understanding of these particular features of dehumidifier drying technology has been very restricted in the past. As a result, the dehumidifier kiln industry has a significant track record of problems that mean that the expectation of low operating costs and simple operation has been frustrated. Some specific examples of the types of problems encountered are listed below:

- The performance of many dehumidifiers, particularly energy efficiency and drying capacity, was below expectations. A basic functioning dehumidifier module is relatively easy to produce, but the design of an effective and reliable unit is more challenging. As a result dehumidifiers of poor design became common in the marketplace. Inevitably, the efficiency and drying capacity of many dehumidifiers was low, leading to long drying times, reduced kiln productivity and higher operating costs. The system reliability was also often low, with gas leakage, and early compressor and heat exchanger failures, leading to significant maintenance costs.

- Recognised equipment suppliers often did not have a good understanding of the special needs for dehumidifier kilns. Few were aware that the performance of dehumidifiers, including the drying rate and efficiency, is sensitive to design and operating practices that have little effect on conventional kilns. The dehumidifier kiln was often seen as being similar to a heat-and-vent kiln, ignoring its lower energy input characteristic. Kiln operators were similarly unaware of the importance of using operating practices developed to meet the needs for dehumidifier kilns.

- Failure to observe key system design and operating requirements almost always lead to reduced drying rates and increased energy use. For example, dehumidifier kiln chambers should be designed specifically for use with dehumidifiers. Poor performance is inevitable in a kiln with inadequate sealing or insulation (Carrington et al. 2000b). Yet such system failures were often attributed to dehumidifier technology (Bates 1995). Similarly, the kiln airflow system should be designed to meet the particular requirements of dehumidifier technology, with greater attention given to reducing fan and airflow losses (Carrington et al. 1999, 2000a).

- In the timber industry, dehumidifiers are currently not seen as providing a better drying service in comparison with conventional technologies. Without doubt, many suppliers of heat-and-vent dryers are content with this perception. In addition it has been difficult to distinguish between different brands of dehumidifiers and to compare the performance with conventional dryers. On the whole, dehumidifier suppliers do not provide enough information on the performance of their systems to enable purchasers to compare models, or to verify that the claimed performance is achieved in practice.

- In the past the environmental benefits attached to the use of an electrically powered dehumidifier kiln, compared with a heated conventional kiln using wood-waste as a fuel, has not been clearly demonstrated. There has been a difficulty that heat pump dehumidifiers use more expensive electricity while heat-and-vent kilns may use relatively cheap fuel sources, such as locally available biomass.

- There is often an emphasis on drying speed ahead of all other factors. For example, the New Zealand timber industry has focussed almost exclusively on the development of high temperature drying practices for the principal New Zealand timber species, radiata pine. For industrial and building lumber grades, radiata pine can be dried under these conditions successfully. Recently, however, the suitability of these schedules for higher value appearance grades of sawn wood has been challenged (Haslett and Dakin 2001). This matter is discussed further below. In the food processing industry, similar issues arise, as there is often considerable pressure to process seasonal crops promptly at the time of harvest.

- The dehumidifier drying industry has remained small and fragmented with individual kiln operators having mixed experiences. The equipment suppliers have not developed a strategic position in relation to competing technologies and have not identified or promoted research on questions relevant to the technology. These include opportunities for enhanced product value, the resolution of environmental issues such as effluent disposal and energy use, and alternative more effective use of biomass resources currently used in drying processes. The potential for drying in modified atmospheres has not been exploited.

- Much of the marketing of dehumidifier dryers has focussed on small, low capital cost installations. This has further weakened the ability for the technology to be promoted in a research and development market that inevitably focuses on the needs of larger players and larger installations.

- Due to industry fragmentation there remains a lack of industry-accepted standards for the specification and benchmarking of dehumidifier kiln energy use and drying capacity. This has meant that there is little protection for users from suppliers of low quality systems. There is no industry supported best-practice for dehumidifier dryers or endorsement of recognised drying schedules for major product groups. There is also little recognition of the impact of factors such as the drying schedule used, and the moisture content of the product, on the overall system performance.

Taking these factors together, it is easy to appreciate why heat pump drying systems in general have remained a specialised application which has generally failed to become accepted as a mainstream technology in the major drying markets (timber, food). While a number of different systems are available on the market, the technology generally remains a minority system. Based on the authors' experience in fielding enquiries, there is a significant level of interest in the use of dehumidifiers for specialist timber applications, especially for difficult-to-dry species such as hardwoods, where the drying rate is determined by product quality considerations. Often this interest is driven by the desire to reduce initial costs, and to provide portability. This is mirrored by interest in specialist food production applications.

3. DEHUMIDIFIER DRYERS IN THE TIMBER INDUSTRY

World sawn timber production in 2000 was 421M m^3, representing some 12.6% of the round-wood harvest (FAO 2001). Approximately 61% of sawn wood was produced by the US (28%), Canada (17%) and the major European producers (16%). The Russian Federation, Brazil and Japan together account for some 13%, in almost equal volumes. To illustrate changes taking place in this industry, we consider the situation in South Pacific countries (Australia, Chile, New Zealand) with expanding plantation forestry. Together these countries currently produce some 3.2% of global sawn lumber.

Forestry is New Zealand's third largest industry, accounting for 4% of its gross domestic product. There are some 1.7 million hectares, 6.4% of land area, of sustainably-managed plantation forest (Statistics New Zealand 2000), 90% of which is in radiata pine. Gross plantation forest production is 19M m^3 pa (per annum) which is increasing at approximately 5% pa. Radiata sawn wood production was 3.9M m^3 in 2000, growing at 7% pa, and kiln dried production is approximately 2.8M m^3 pa. In 1998 there were some 480 timber kilns operating in New Zealand, 95 of which were heat pump dryers, with typical drying times of 15 days. Heat pump kilns produced some 2.8% of dried lumber in New Zealand (Simpson 2001). The total volume of sawn timber production in Australia is similar to New Zealand, but there is a high proportion of hardwood, which is planned to increase further. The production of sawn wood in Chile is 5.7M m^3 pa. Chile has a significant and growing radiata pine plantation forest industry.

Radiata pine responds well to intensive management, much of it taking less than 30 years to mature for milling purposes. There are three main end-uses: appearance, structural and industrial. To achieve a rapid throughput and quick return of capital, the latter two grades are typically dried at high-temperatures (120-140°C), leading to a drying time less than 24 hours from green at 140% mc (moisture content, dry basis) to dry at 12% mc. These conditions are inaccessible for dehumidifier dryers. However, opportunities are emerging at the quality end of the timber market. Driven by export demand and the increased value of managed plantation timber sources, the timber industry is increasing its efforts to target the market for high quality appearance grade wood. On the basis of value per cubic metre of timber, these grades have the potential to fetch a substantial premium compared with lower quality timber, often by a factor of more than ten. In terms of drying methods, the main current method for drying appearance grades is to use conventional kilns to dry at 90°C, followed by a period of reconditioning for stress relief, normally by steaming. The total duration of the drying process is typically 2-3 days.

The demand for increased quality provides a new opportunity for dehumidifier kilns, since the present drying technology suffers from a number of difficulties in terms of the quality achieved for appearance grade radiata pine. There are the usual challenges of controlling the final moisture content and residual stresses to within grade specifications. Timber produced by slower dehumidifier dryers is more consistently within the required final moisture content window than that produced by conventional dryers (Simpson 2001). However dehumidifiers are less successful in achieving the target stress levels, because dehumidifier kilns in New Zealand normally do not have reconditioning facilities. Recently further difficulties have been recognised for conventional drying practices. Predominant among them are two forms of timber degrade:

- Chemical discolouration near the surface of dried sapwood, called *kiln brown staining*. As a result, a surface layer of the dried lumber, typically 2 mm thick, must be removed in appearance grade boards. This creates costs due to additional processing and the waste of product in which there are sunk costs for milling and drying. The colour intensifies with increased drying temperature, so that low temperature dehumidification drying reduces the intensity and depth of the stain.

- Checks, or internal cracks, called *within-ring internal checking*. Because the cracks are internal to the board, they are not detected prior to further processing. This defect therefore represents a major loss for the remanufacturing industry. Indications are that, although primarily resource based, internal checking is aggravated by increased drying temperature and the drying rate.

These defects result in the discounting for radiata pine relative to competing species in the international market. At present no economically effective methods have been found for the prevention or removal of these defects, other than to dry appearance grades more slowly at reduced temperatures (Haslett and Dakin 2000). Industry sources suggest that the price premium achievable for high quality radiata pine with good colour and low risk of internal checks, while also meeting accepted standards for moisture content, uniformity and internal stress, is on the order of $US150/m^3, a value increase of approximately 35%. This is an example of the opportunities for the dehumidifier supply industry for high quality drying facilities.

4. DEHUMIDIFER DRYERS IN THE FOOD INDUSTRY

Heat pump dehumidifier use in the food industry tends to be targeted at particular specialised areas, such as "semi-dried" tomato products, dried gelatine products, fruit (eg mangos), nuts, and vegetables. These products feature significantly in Australia. In Scandinavia there is a well established fish drying industry based on the application of heat pump drying technology, possibly the most successful application of its type. The special low temperature low humidity capabilities of heat pump dryers are significant here. Dehumidifiers operating under such conditions have been applied in the production of live seed and pollen, demonstrating product values exceeding $US500 per kg (Chen et al 2002a). Mason et al. (1994) reviewed the application of heat pump dryers in the Australian food industry. Based on their experience, they estimated 30 heat pump dryers were in use in the food industry at that time. There has since been a steady adoption of the technology, which suggests the actual number currently in use in Australia is in the range 50–80, each with typical moisture extraction rates of 500 – 1000 kg/day.

Relative to the timber industry, the application of dehumidifiers to the food industry poses a number of additional challenges. Food crops are typically processed on a seasonal basis, close to source, leading to significant pressure for low-cost, low-technology approaches that are not necessarily compatible with good dehumidifier technology. A basic installation can be as simple as a cupboard with some trays of product and a domestic dehumidifier; such installations clearly reflect a lowest capital cost approach. By contrast, the upper end of the market insists on a high level of multi-disciplinary integration to create a total product of which a dehumidifier drying process is but a small part. Thus a controlled atmosphere drying process for apricots, for instance, has to integrate system design and operation with questions of preservative use, product appearance, marketing, packaging, transport and shelf life. The need for product-specific solutions of this nature makes the technology development path complex and often too expensive to pursue, except on a very large scale.

5. POTENTIAL IMPACT

Dehumidifier dryers have a role in reducing primary energy consumption and greenhouse gas emissions in drying processes. The total impact across all industries is difficult to calculate because of the diverse products and technological adaptations involved. However it is possible to provide indicative calculations based on the timber industry.

Table 1. Estimates of energy use in radiata pine drying operations (Bannister et al. 1997).

Fuel/Kiln types	Conventional Coal-fired Kiln (GJ/ m^3)	Conventional Gas-fired Kiln (GJ/ m^3)	Dehumidifier Kiln (GJ/ m^3)
Fuel	2.4	2.2	-
Electricity	0.3	0.3	0.6
Total Site Energy	2.7	2.5	0.6
Primary Energy	3.3	3.1	1.8

Bannister et al. (1997) presented a case study of the use of a dehumidifier drier for drying radiata pine, based on numerical simulation of a commercial design. The performance of the dehumidifier kiln was compared with two fuel fired kilns, which were equivalent to the dehumidifier in terms of annual throughput. The analysis indicated that an average specific moisture extraction rate of 3.6 kg/kWh was feasible and practical for the dehumidifier kiln, corresponding to an electrical energy use of 0.6 GJ/m^3 for radiata pine dried from an initial moisture content of 140% to 12%. For the equivalent conventional kilns the energy requirement was between 2.5 and 2.7 GJ of on-site energy. Table 1 summarises the estimates for the primary energy demand for the three kilns, allowing for the electricity demand to be met by conventional thermal generation at 33% efficiency, using fossil fuel. The primary energy saving for this particular case was 1.3 GJ/m^3 compared with the gas-fired kiln, and 1.5 GJ/m^3 relative to the coal-fired kiln. Similar energy savings are feasible in the drying of hard-woods (Carrington et al. 1999).

The effect of greenhouse gas emissions was also evaluated by Bannister et al. (1997), as shown in Figure 4. For this particular application, there are significant reductions in greenhouse gas emissions, subject to good control of refrigerant losses, in this case R134a. The reduction in greenhouse gas emissions was of the order of 150 kg-CO_2/m^3 relative to a conventional kiln heated using coal as the fuel. Relative to a gas fired conventional kiln, the reduction in greenhouse gas emissions was in the range 0–50 kg-CO_2/m^3. To estimate the environmental impact of a dehumidifier kiln replacing a conventional kiln which uses wood-waste as fuel, additional assumptions are required to deal with the mix of direct heat generation and the opportunity for combined heat and power processes in use.

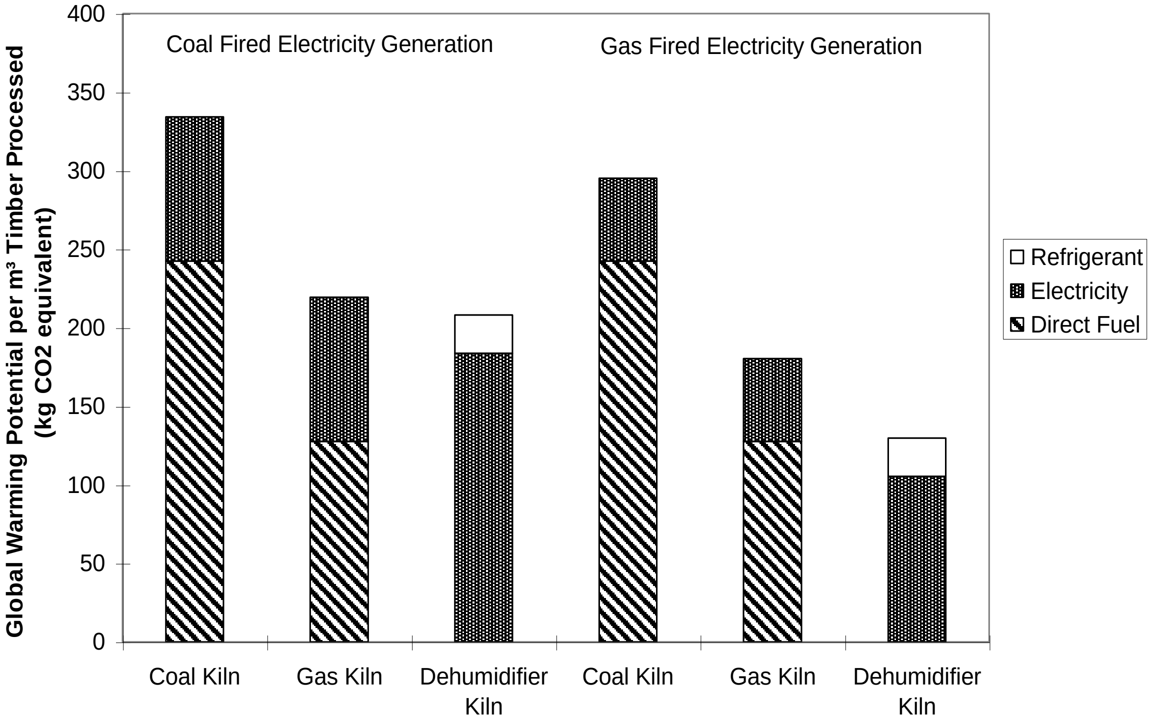

Figure 4. Greenhouse gas emissions for different timber drying dryers, based on short term (<20 years) global warming potential (Bannister et al. 1997).

While this analysis is specific to the kilns considered, it provides a basis for estimating the scale of potential savings in primary energy and greenhouse gas emissions through the wider use of dehumidifier drying technology. It should be borne in mind that there are few options for improving the energy efficiency of conventional drying technology. On the other hand, feasible increases in the energy efficiency of heat pump dehumidifier technology, through systematic optimisation, could raise the kiln specific moisture extraction rate to 5 kg/kWh, corresponding to a further reduction in primary energy demand by some 30%. Accordingly we shall regard the performance data provided by Bannister et al. (1997) as conservative estimates, providing a reasonable basis for assessing the global potential for reducing primary energy use and greenhouse gas emissions in terms of CO_2 equivalents. The assumptions and estimates are summarised in Table 2.

Table 2. Potential reduction in annual global primary energy use and greenhouse gas emissions through use of heat pump dehumidifier technology in the wood drying industry.

Assumptions	
Global annual sawn timber production (2000)	421×10^6 m^3
Fraction of sawn timber production kiln dried	0.7
Primary energy saved through use of dehumidifier technology	1.4 GJ/m^3
Potential greenhouse gas emission reductions	100 kg-CO_2/m^3
Uptake of dehumidifier technology	100%
Estimates	
Potential for reduction in global primary energy use	417 PJ pa
Potential for reduction in greenhouse gas emissions	30 M tonnes-CO_2 pa

To achieve complete saturation of this market would require some 200,000 kiln units, assuming a typical unit to have a timber capacity of 50 m^3 and produce 30 dry charges per annum. This is a large market compared with our estimate of current world dehumidifier kiln production of 500 – 1000 dehumidifier kilns per annum. On this basis the annual increase in capacity would be sufficient to process less than 0.5% of estimated global kiln-dried timber production.

6. PROGRESS IN RESEARCH

At the dehumidifier level research has focused on the use of heat recovery systems, the utilisation of more efficient and reliable compressors, and the impact of system sizing on performance. Using R134a, a dehumidifier specific moisture extraction rate as high as 7.94 kg/kWh has been achieved under favourable conditions, although there appears significant scope for further improvements (Bansal et al. 1997).

At the system level, numerical simulation methods have received significant attention (Jolly et al. 1990, Prasertsan et al. 1996, Chou et al. 1994, Carrington et al. 2000a). This is necessary, since semi-closed systems such as dehumidifier dryers exhibit strong interactive feedback processes, and therefore multiple-iteration calculations are required to determine refrigerant and air states. A dynamic model may also be required, as the conditions within a batch-mode dehumidifier change continuously throughout the drying process (Sun et al. 1999, 2000, Carrington et al. 2002).

To improve overall energy efficiency dehumidifier design must also be optimised in the context of its application, taking account of the relevant product information and process requirements (Carrington et al. 1999). Experience has shown that the potential of the technology will not be fully realised unless the dehumidifier and the operational procedures are well integrated (Bannister et al. 1999). For this purpose, the drying process and associated product transport properties suitable for dehumidifier dryers are being derived for a wide variety of products, including timber, fruit and other food (Davies et al. 2001).

As software models are validated they are used with increasing confidence for commercial dehumidifier system design. Accurate prediction methods enable precise design, giving improved assurance of unit performance, more reliable sizing of equipment and reduced operating costs. Several prototype dehumidifiers for specialist applications have also been built in New Zealand, achieving good outcomes for clients (Barneveld et al. 1996; Chen et al. 2002a). Based on this knowledge, a new modular design of dehumidifier is being assessed at a commercial site (Carrington et al. 2001). An operational guideline has been developed for use by dehumidifier timber kiln operators (Bannister et al. 2002) and strategies for stress relief in dehumidifier timber dryers are being investigated (Pearson and Haslett 2001). There is also an increased level of acceptance in the industry for dehumidifier timber drying technology. One manufacturer in Auckland was reported to have supplied over 50 dehumidifier kilns in New Zealand in 2000–2001. However, enhanced product quality and value is not yet a significant factor for most dehumidifier users in the New Zealand timber industry. In a recent survey the primary selection criteria cited by users of dehumidifier kilns were: lower plant costs, faster drying and higher efficiency (Chen et al. 2002b).

Newer areas of research are also being explored, including controlled atmosphere drying of fruit and foods (Chen et al. 2000). Significant improvements in product attributes have been reported for this technology (O'Neill et al. 1998). However, penetration of food product markets by dehumidifier technology appears to be significantly reliant upon a greater understanding of sector needs, and a multi-disciplinary approach to the generation of new, value added products enabled by dehumidifier dryers. Dehumidifier technology is also being combined with other technologies, including solar dryers and fluidised-bed dryers, and is used to dry other bio-materials.

7. CONCLUSIONS

Drying is an important process in many industries, in particular the forestry, agricultural and food processing sectors. This paper has reviewed some of the recent research and technology development in this area. It has been argued that heat pump dehumidifiers are one of the most promising technologies in improving product quality and reducing energy consumption of drying, particularly for high value products requiring a well-controlled drying regime. It has been shown that the potential global reductions in greenhouse gas emission using heat pumps dryers are significant.

Progress has been made in research and development of dehumidifier drying technology, particularly in understanding and effective integration of systems and system components to achieve assured and efficient performance. There now also appears to be an increased level of acceptance in the industry for dehumidifier drying technology. To achieve impact, the link between research, manufacturers and operator end-users needs to be strengthened. At the same time, the industry must improve its approach to design integration and establish clear demonstrable benefits in a form that can be understood by the relevant production industry sectors.

8. ACKNOWLEDGEMENTS

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