Design of a Solar-Assisted Heat Pump Combined Drying System and Optimization of Segmented Drying Process for Veneer

H. Zhao
Southwest Forestry University– China
M. Li
Yunnan Normal University– China
W. Li
Southwest Forestry University– China

Introduction

Veneer drying accounts for 60%–70% of total energy consumption in plywood production [1,2]. Traditional biomass furnaces suffer from low efficiency and high emissions [3]. Solar-assisted drying offers a renewable alternative, but conventional systems are limited by low temperatures (40–70°C) and weather dependence [4,5]. Therefore, integrating solar preheating with heat pump systems provides a viable pathway to enhance drying efficiency and achieve stable, high-temperature operation [6].To address these challenges, this study proposes and experimentally investigates a solar-assisted heat pump multi-energy complementary drying system specifically designed for veneer drying applications. By integrating solar thermal energy with heat pump technology, the proposed system aims to overcome the limitations of conventional single-source drying methods, such as high operational costs during non-sunny periods and insufficient drying temperatures in heat pump-only systems. A key contribution of this work is the development of a three-stage temperature gradient drying process, which is designed to balance drying rate and product quality while minimizing energy consumption. The stages are as follows: (1) a preheating stage at 40–50 °C to gently raise the material temperature without causing thermal shock; (2) a constant-rate drying stage at 60–70 °C with a relative humidity (RH) maintained between 40% and 50% to ensure efficient surface moisture evaporation while avoiding case hardening; and (3) a final equalizing stage at 100–120 °C with an RH below 30% to eliminate residual internal moisture gradients and stabilize the veneer.

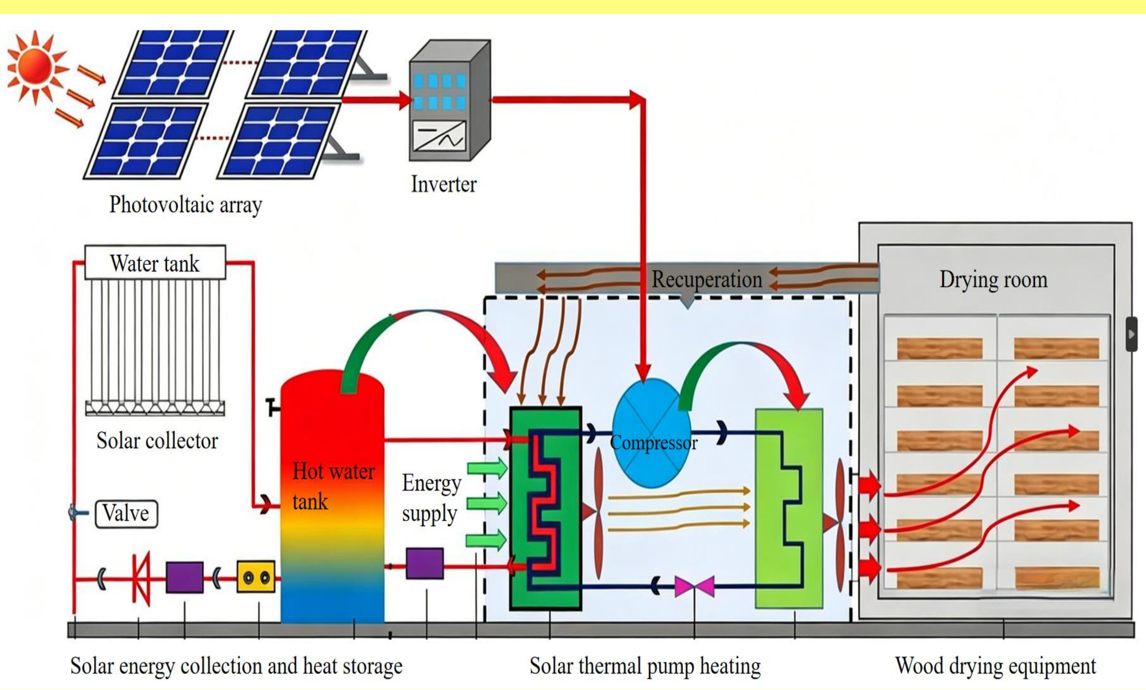

Fig. 1. Scheme of the experimental installation.

Construction of the system

This integrated veneer drying system combines solar photovoltaic (PV), solar thermal, and air-source heat pump technologies in a synergistic multi-energy complementary configuration. Solar PV panels generate electricity, which is converted via an inverter to power the heat pump compressor and auxiliary equipment. Meanwhile, flat-plate solar collectors heat water stored in a thermal tank, which is then circulated through a composite evaporative heat exchanger to regulate the temperature of the drying chamber or the heat pump evaporator. Simultaneously, the heat pump operates in a vapor-compression cycle using ambient air as the low-grade heat source, where the condenser delivers high-grade heat to the drying chamber and the evaporator recovers sensible and latent heat from the exhaust return air, significantly enhancing overall energy efficiency. This hybrid configuration enables cascaded utilization of solar thermal and ambient thermal energy, reducing the heat pump's electrical power consumption while maintaining stable drying temperatures. Consequently, the system improved operational resilience under fluctuating weather conditions.

Inside the drying chamber, veneer sheets are stacked on racks and dried under precisely controlled airflow conditions, with temperature and relative humidity dynamically regulated by the coordinated action of the heat pump and the solar-heated water loop to ensure uniform moisture removal and minimize defects such as warping or cracking. The staged temperature profile—preheating, constant-rate drying, and equalizing—is automatically executed by the control system, which adjusts the heat pump's compressor frequency and the water circulation rate based on real-time feedback from embedded sensors. This ensures that the drying rate closely follows the moisture diffusion capacity of the veneer, preventing excessive surface evaporation that could lead to case hardening or internal cracks. An intelligent control layer, including a water tank temperature controller, circulation pumps, and an expansion valve, optimizes real-time energy allocation between solar thermal and electrical inputs according to solar irradiance and process demands. The system prioritizes solar thermal energy when available, seamlessly switching to heat pump mode during periods of low irradiance or nighttime operation, thereby maximizing renewable energy utilization without interrupting production. This enables stable, high-performance operation with a solar fraction exceeding 35% and energy savings of more than 30% compared to conventional biomass-fired systems. Long-term testing confirms that the proposed system maintains consistent drying quality and energy efficiency across seasonal variations, offering a robust and scalable solution for sustainable veneer processing in off-grid or semi-rural industrial settings.

Results

Fig. 2 shows the moisture content reduction curves of veneer samples under conventional heat pump drying and solar preheating drying. In the conventional drying group, the moisture content decreased slowly from 80.3% to approximately 26.7% after 7 hours. In contrast, the solar preheating drying group exhibited a significantly faster drying rate, with moisture content dropping from 86.0% to 28.7% within 6 hours. This accelerated moisture removal can be attributed to the preheating effect of solar energy, which raises the initial temperature of the veneer and reduces the thermal load on the heat pump, thereby enhancing overall drying efficiency. Additionally, the solar preheating group demonstrated a more consistent moisture reduction trend throughout the process, indicating better process stability and reduced risk of localized over-drying. The results indicate that the solar preheating method effectively accelerates the drying process, shortening the drying time by approximately 14.3% under the same final moisture content conditions.

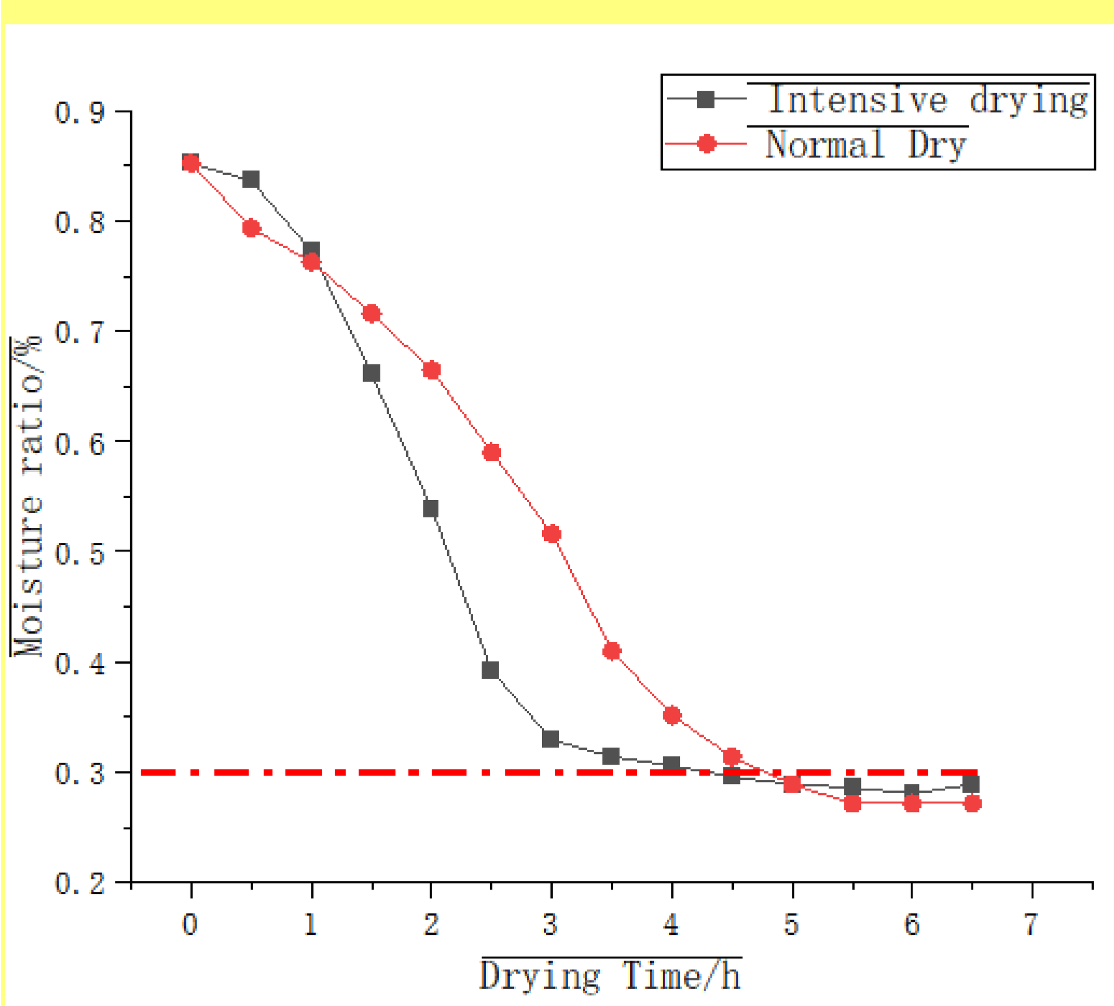

Fig. 2. Comparison of drying kinetics and energy consumption between two drying modes.

Fig. 3 presents the total drying energy consumption for the two drying methods. The conventional heat pump drying group consumed 514.1 kWh, while the solar preheating drying group consumed 412.6 kWh, representing a reduction of 101.5 kWh. The corresponding energy saving rate is approximately 19.75%. This significant reduction in energy consumption is primarily due to the solar preheating stage, which raises the initial temperature of the veneer and reduces the workload of the heat pump compressor. Furthermore, the integration of solar thermal energy allows the heat pump to operate under more favorable conditions, maintaining a higher coefficient of performance (COP) throughout the drying process. The improvement in energy efficiency is attributed to the reduced thermal load on the heat pump and the more efficient moisture removal enabled by the staged temperature gradient, which shortens the overall drying time and lowers total energy input.

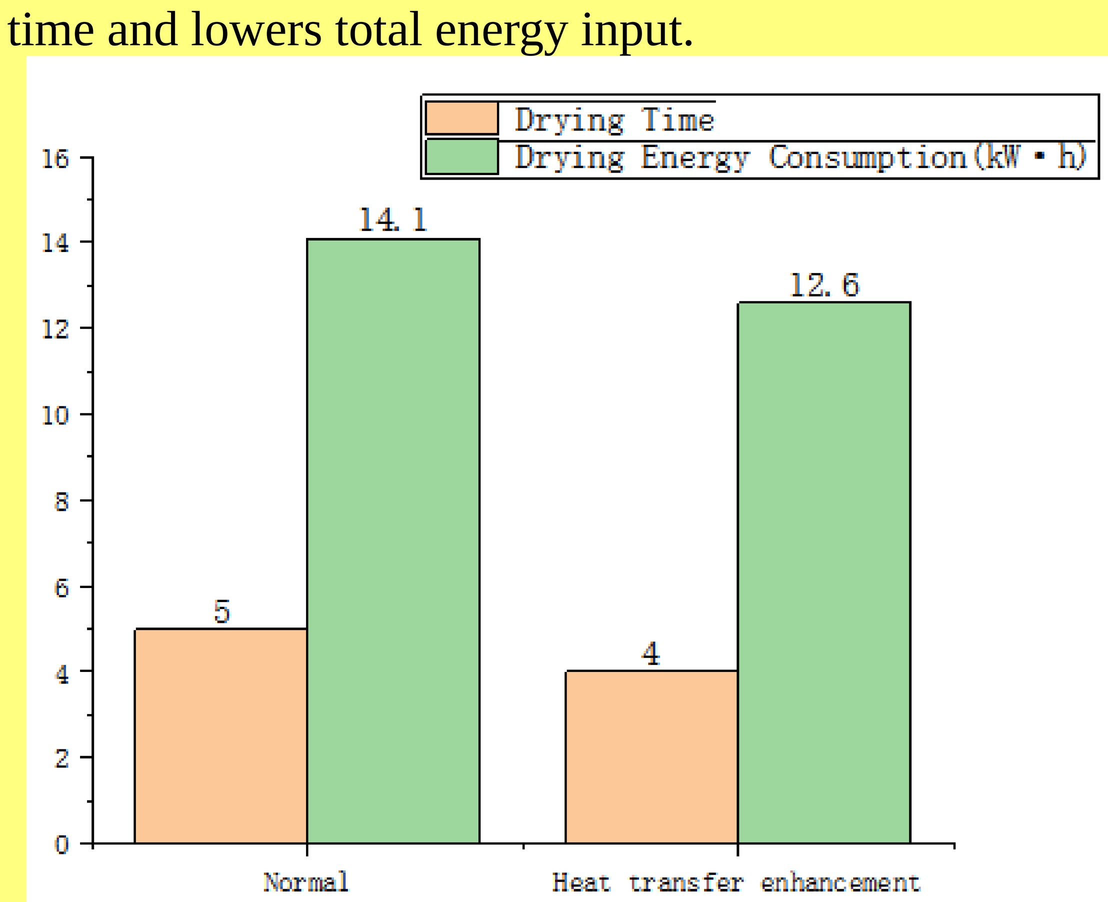

Fig. 3. Comparison of drying energy consumption between conventional and enhanced drying.

Conclusions

Compared with conventional heat pump drying, the proposed solar preheating mode reduced drying time by 14.3% and energy consumption by 19.75%. Relative to traditional biomass-fired drying systems, the energy savings exceed 30%, with a solar fraction of 35%. Furthermore, the warping deformation rate was reduced by 25%, and the final moisture content of the dried veneer reached 8%–12%, meeting industrial quality standards. This study provides a technical reference for solar-assisted wood drying applications.

References

[1] Journals Xu, B., et al., Selection of drying techniques for Pingyin rose on the basis of physicochemical properties and volatile compounds retention. Food Chemistry, 385: p. 132539 (2022).
[2] Journals Shi, M., et al., Flow field analysis and design optimisation of Tibetan medicine double heat pump drying room. Computers and Electronics in Agriculture, 199, 107141 (2022).
[3] Journals Chinnasamy, S. and A. Arunachalam, Experimental investigation on direct expansion solar-air source heat pump for water heating application. Renewable Energy, 202, 222-233
[4] Journals Aktas M , Sevik S , Amini A ,et al.Analysis of drying of melon in a solar-heat recovery assisted infrared dryer. Solar Energy, 2016, 137, 500-515.
[5] Journals Ghoname M S , Darwesh M R , Noiser E S ,et al.Comparison between the drying properties of seedless grapes, natural solar drying and microwave drying[J].Journal of Sustainable Agricultural and Environmental Sciences, 2024, 3(4), 54-58.
[6] Journals Kidane H. Enhancing the drying uniformity in solar drying systems: Computational and experimental study. International Journal of Thermofluids, 2025, 29, 101408.