Predicting performance of cooking ovens: A simulation-based design

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Research Justification
Convection ovens provide a versatile way of cooking different food groups in households and professional kitchens. However, their thermal efficiency is very poor (about 13%). Oven cooking involves coupled radiative and convective heating of food as a porous material, which undergoes a complex thermophysical transformation. Engineering understanding of the energy fields in an oven is limited, making it challenging to design smart, energy-efficient ovens that provide the desired performance metrics of cooked food; such design ends up largely based on trial-and-error.

Objective
To provide a mechanistic understanding of the effect of oven parameters (broil/bake/convective heating element temperatures, air flow rates, position of racks/food in multi-rack cooking, duty cycle) on the food boundary conditions deciding the success of cooking.

Methods
A physics-based computational model for a conventional oven with conduction, convection, and radiation modes of heat transfer is developed. The coupled system of governing equations for multicomponent, multimode heat transfer and fluid flow inside the oven cavity is solved numerically. The model predicts the evolution of wall temperatures, air temperatures and air velocities inside the oven cavity during the preheating and cooking cycle. The oven model is validated by comparing the predicted cooking metrics (desired air temperatures, air velocities, radiative heat flux) against measured values.

Results
The predicted wall temperatures, air temperatures and air velocities inside the oven cavity for preheating and cooking cycles agreed very well with the experiments. The air temperatures inside the oven cavity showed nearly 40°C variations and were stratified with higher temperatures close to the bottom surface. The radiative heat from the bottom wall was 37% more than the top wall inside the oven cavity. The model showed that the middle rack was the most optimal cooking rack with desired air temperatures. The size of the optimal cooking zone was reduced with a higher thermal (food) load.

Conclusion
The model enables a detailed quantitative understanding of the influence of oven parameters on cooking metrics, thus providing a rational basis for design change. The mechanistic model will allow more efficient design and optimization of ovens, reducing time to market, and enabling novel improvements.