# Data-driven approach for reducing variability in chemical vapor deposition of carbon nanotube forests based on dynamic cycling of temperature and pressure

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Run-to-run variations have been commonly cited as a big challenge in growing carbon nanotube (CNT) forests by chemical vapor deposition (CVD). Based on the hypothesis that growth inconsistency originates from uncontrolled variations in the concentration of $O_2$, we tested the effect of various factors on growth consistency. Four factors were studied: (1) pumping to low pressure before catalyst formation, (2) additional low-pressure pumping with mild baking at 200 °C before catalyst formation, (3) the temperature of the reactor when it is opened (hot open vs. cold open) after the baking recipe ends, and (4) the ratio of He to $H_2$ during the catalyst formation step. We designed 11 growth recipes and statistically analyzed the height of 95 CNT forests. As a measure of consistency, we used coefficient of variation (CV) of forest heights among samples grown using the same recipe. Statistical analysis demonstrated that only the pumping with mild baking at 200 °C led to statistically significant decrease in CV, confirming higher consistency. Atomic force microscopy of the catalyst-coated substrate after different catalyst formation steps showed that although the low-pressure mild baking led to smaller particles, there was no significant difference in CV of particle sizes. This suggests that variability in growth was primarily caused by variations of catalyst chemical state

rather than variations of particle size distributions before growth starts. The mild low-pressure baking approach described in our work is applicable to other CVD synthesis of nanomaterials such as graphene and various nanowires.